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# THE CONDUCTION OF ELECTRICITY THROUGH GASES

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# THE CONDUCTION OF ELECTRICITY THROUGH GASES

BY

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WITH A GENERAL PREFACE BY

O. W. RICHARDSON, F.R.S.

YARROW RESEARCH PROFESSOR OF THE ROYAL SOCIETY

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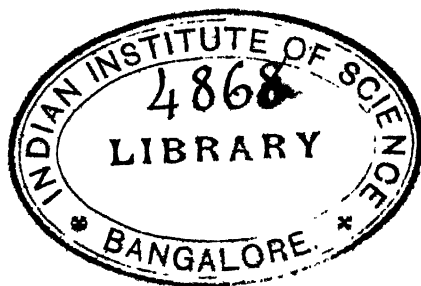
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O. W. RICHARDSON

KING'S COLLEGE
*June, 1928*

# PREFACE

IN this book I have attempted to give an outline of the main phenomena which can be studied quantitatively in connexion with the passage of electricity through gases at low pressures, in particular those associated with the glow-discharge. No references to original papers have been made in the text, but it will be obvious that I have made considerable use of the monographs and papers mentioned in the Appendix. I am indebted to my colleagues Miss N. M. Carmichael and Mr. W. L. Brown for reading and criticizing parts of the typescript, and to Messrs. the Hewittic Electric Co., Ltd., for kindly supplying a photograph from which Fig. 23 was prepared.

K. G. E.

*February, 1929*

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# THE CONDUCTION OF ELECTRICITY THROUGH GASES

## CHAPTER I

## INTRODUCTION

### 1. The Glow Discharge

WHEN a gradually increasing electric field is applied between two electrodes in a vessel ontaining gas, only a minute current passes until the pplied potential exceeds a certain minimum value, ermed the Sparking Potential. The transport of lectricity, once the insulating power of the medium ıas been overcome, is accompanied by a characteristic mission of radiation from the discharge tube, which ften assumes a very beautiful appearance. Originally natters of scientific curiosity, the various forms of lischarge have now become of much importance, both s a field for research on the intimate structure of matter nd in numerous technical applications.

If the gas is at atmospheric pressure, the discharge akes the form of a tortuous spark, which is often ›ranched away from the positive pole, and is essentially he natural phenomenon of lightning. The applied ›otential must be high; and when the gas is air, the ritical field is about 30,000 volts per centimetre. On educing the pressure, the sparking potential becomes ess, and at the same time the conducting path becomes

more diffuse, and may ultimately occupy practically the whole of the containing vessel. When a pressure of a few centimetres has been reached, a dark layer, the Faraday dark space, can usually be distinguished separating a cushion of light on the cathode, the negative glow, from the positive column of light which extends to the anode. The pressure at which this is first seen, and the luminosity of the positive column, depend on the nature of the gas, and the distance apart of the electrodes; particularly at the higher pressures, the positive column is often almost non-luminous, and there is merely a glow representing it at the surface of the anode. The negative glow and Faraday dark space expand and move towards the anode when the pressure

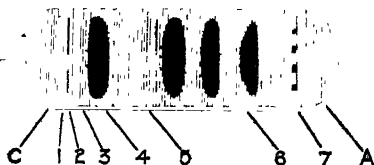



FIG. 1.—Glow Discharge.

is further lowered, whilst the negative glow in turn is now seen to be separated from the cathode by the Crookes or cathode dark space. A luminosity—the cathode glow—usually persists within the latter immediately against the surface of the cathode, and is in some instances separated from the electrode by a thin and intensely dark primary dark space.

The typical appearance of a tube under these conditions is shown in Fig. 1. It is supposed to contain a mixture of helium and neon, with a trace of mercury vapour, at a total pressure of about three-quarters of a millimetre of mercury, and to be passing a current of about one milliampere at a potential difference of about 375 volts. Starting from the cathode (C), there is first a well-marked primary dark space (1). The

reddish cathode glow (2) fades gradually into the main cathode dark space (3), which is about 4 millimetres across. The negative glow (4), which is orange, has a maximum of intensity close to its negative boundary, but fades off diffusely on the other side into the Faraday dark space (5). The positive column (6) is built up of striae, which have a sharp blue boundary at their negative faces, and a diffuse orange boundary on the opposite side. The surface of the anode (A) is partly covered with irregularly disposed orange-coloured balls of light (7). If the electrodes are moved together, the effect is simply that the anode and anode glow move through and annihilate the pre-existing light structure, the residual striae undergoing simultaneously small changes in relative position. Ultimately the anode glow disappears when the anode is somewhere in the Faraday dark space, and the discharge is extinguished as soon as the anode penetrates into the cathode dark space. The latter is evidently the most important agent in determining whether the gas shall insulate or conduct, and almost the whole fall in potential between the electrodes occurs across it. The dark spaces, excepting possibly the primary one, are only relatively non-luminous, and the dimensions and appearance of the various parts depend upon the electrical conditions and the nature and pressure of the gas.

The most important variation of what has been described is that the positive column is sometimes uniformly luminous, absence of striae being associated in general with the higher gas pressures and currents, and with freedom of the gas from impurity. When the cathode is not flat, the form of its surface is closely reproduced by the contours of the cathode glow and of the adjacent boundary of the negative glow, but the positive end of the tube, beyond the Faraday dark space, is almost unaffected. If the cathode is incandescent, the cathode dark space and much of the cathode fall in potential vanish, and there is danger that the current will increase largely, if it is not limited by

having a suitable resistance between the source of potential and the tube, and will pass from the form of a glow-discharge into that of an arc.

At still lower pressures, the discharge again passes less readily. The increase in the sparking potential is accompanied by an expansion of the cathode dark space, and bluish streamers can be detected proceeding through the negative glow towards the anode, constituting the cathode rays of the earlier investigators, now known to be beams of electrons which have their origin in the cathode dark space. At the same time, luminous streams of positive rays can be seen to pass through a perforation in the cathode in the opposite direction. Ultimately potentials of 25 Kilovolts or more may be needed to run the discharge. The cathode dark space then fills the tube, if this is not too large; the walls fluoresce, and are, together with the anode, a source of X-rays, the arrangement being essentially that employed in the older forms of gas-filled bulbs (see B. L. Worsnop's *X-Rays* in this series). In general, the lower the pressure, the larger must the apparatus be to exhibit any particular discharge phenomenon which depends upon the pressure.

This brief description of the glow-discharge will be elaborated subsequently, but from what has already been said it is evident that the processes which come into play are complicated. There are nevertheless two immediate inferences that may be made, viz., that excited atoms are present in the gas, to emit radiation, and that ions and electrons are present, to conduct the current. The conditions under which they are produced can be studied more satisfactorily with tubes of simpler design.

## 2. Excitation and Ionization

If electrons from a hot filament F (Fig. 2) are projected into a hollow metal box B through a gauze window in the base of the latter, the visible effects produced can be observed through gauze windows at the side. If

te electron current from F is sufficiently small, the hole of the interior of B is at one potential, and the ectrons, in so far as they do not lose energy by collision, ierefore move about within it with the energy acquired any potential difference between F and B, which in be varied by an external battery and potentiometer. o take a definite example, somewhat idealized, if the pparatus contains the vapour of sodium, no light opears within B until the potential difference is 2·1 olts, when the yellow D lines at 5890 A and 5896 A iddenly flash up. With larger differences in potential, ie intensity of these first increases, and then other nes come up one after another. The explanation of

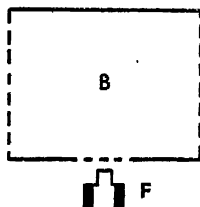



FIG. 2.—Simple Apparatus for Excitation of Spectra

iis is that an electron rebounds elastically from an tom of sodium only if it has less energy than is acquired i a free fall through 2·1 volts. At this speed, some f the collisions cease to be elastic, and result in the ransfer of the whole of the energy of the electron to sodium atom. In its subsequent return to the normal tate, the atom emits a monochromatic train of waves f a frequency $n$ which is given by the equation

$$E_1 - E_0 = hn \quad . \quad . \quad . \quad . \quad . \quad (1)$$

here $E_1$ is the energy of the atom in its excited state 2·1 electron-volts), and $E_0$ its energy when unexcited, hich is conveniently taken to be zero. $h$ is Planck's niversal constant, which has a numerical value of ·56 $10^{-27}$ erg-secs. For many purposes it is convenient

to express the energy in terms of the number of volts (V) through which an electron would have to fall freely to attain it, by the relation

$$eV = E = hn \quad . \quad . \quad . \quad . \quad . \quad (2)$$

in which $e$ is the electronic charge, or alternatively to measure E by the wave-length in vacuo ($\lambda$) which corresponds to the frequency $n$. Employing Ångstrom units ($10^{-8}$ cm.) and volts,

$$\lambda V = 12330 \quad . \quad . \quad . \quad . \quad . \quad (3)$$

2·1 volts is the Excitation Potential of sodium; two lines appear in this case because a sodium atom has

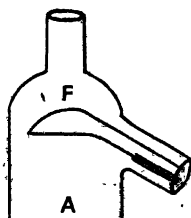



FIG. 3.—Tube for obtaining a Discharge through Mercury Vapour

the two excited states of almost identical energy. Line spectra come from atoms, band spectra from molecules.

Rather more complicated conditions under which light can be produced can be demonstrated by the luminous effects produced on passing a current of electrons from a hot filament F (Fig. 3) to a mercury surface A, which constitutes the top of the liquid in the Torricellian space of a barometer. This is jacketed by a furnace to keep the pressure of the vapour at a convenient value. Green striae appear in the interspace, and their number increases with the difference in potential between F and A, but is independent of the position of the mercury, movement of which merely

affects their distance apart. This discharge differs from that described in § 1 in that the current is almost identical with that from the filament in absence of the mercury vapour, and that the discharge ceases when the filament is cool. It is found that a new striation appears for each increase in potential of 4·9 volts. As before, the explanation of this is that an electron rebounds elastically from an atom of mercury only if it has less energy than would be acquired in a free fall through this difference of potential. The electrons leave the filament with small speed, and diffuse towards the anode in the electric field, making on the way numerous collisions which are at first elastic. Because the mass of an electron is only $3\ 10^{-6}$ that of a mercury atom, each of these involves only a minute transfer of energy, so that at any point the electron has a kinetic energy specified by the electric potential at the point, although it is not necessarily moving in the direction of the electric field at the moment. At the 4·9 volt equipotential surface some of the collisions cease to be elastic and the whole of the energy of an electron is transferred to a mercury atom. The subsequent processes are less simple than with sodium, but the main action is probably that some of the excited atoms go to form mercury molecules ($Hg_2$), and that in the subsequent return of these to the state of normal atoms, the system proceeds through a set of discrete states, each of which is associated with a definite energy. In passing from one to another of these, radiations are emitted according to equation (1), and the net effect of these is the green light of the striae. In this experiment, the pressure of the vapour is such that almost all the electrons are reduced to rest by inelastic collisions in the first striation; this thus serves as an effective cathode for the second, this in turn for the third, and so on. Since there is no new formation of electrons in the gas, it is obvious why the current is the same as from the filament when striae are not present.

Similar excitation can also take place under the

influence of radiation, when the energy of the quantum of the latter ($h\nu$) must again be not less than 4·9 electron-volts. In mercury vapour, an uncombined atom which had been excited by energy of 4·9 electron-volts could only return to its normal state in a single jump, with emission of ultra-violet light of wave-length 12330/4·9 or 2537 A, and when mercury vapour at low pressure is irradiated with not too intense monochromatic radiation of this frequency, it is in fact found that visible radiation is not produced, but only ultra-violet Resonance Radiation of the same wave-length as that which is being used for excitation.

When an electron collides with an atom or molecule with somewhat greater energy than is merely required for excitation, a more drastic action may occur, and

FIG. 4.—Electrode System of Soft Valve

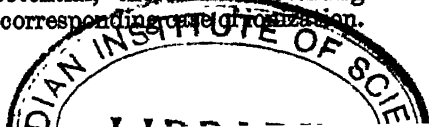
an electron be actually ejected from the atom or molecule, leaving a positively charged ion behind. There is again a certain critical Ionization Potential for each substance. This can be readily shown with a commercial 'soft valve', a three-electrode system similar to the ordinary evacuated thermionic tube used for radio-telegraphy, but containing gas instead of being highly exhausted. We will suppose that one of these containing neon at the convenient pressure of about one-third of a millimetre of mercury is set up with the grid (G, Fig. 4) made positive with respect to the filament (F), and the anode (A) negative, so that no electrons can reach the latter. On raising the potential of the grid,

it will be found that no current passes to the anode until the grid potential is 21·5 volts, when the anode starts to receive a current of positive ions. These have been formed by collisions of electrons having energy of 21·5 electron-volts with neon atoms near the grid, and have been drawn to the anode by the field between the two. A number of critical potentials found by these and other methods are collected in Table I; where a substance has more than one excitation potential, as is usually the case, the lowest has generally been given.

TABLE I.

Excitation Potential ($V_r$) and Ionization Potential ($V_i$) for various Substances, expressed in Volts

| Gas | He | Ne | A | $H_2$ | H | Hg | Na | $N_2$ | $O_2$ |
|---|---|---|---|---|---|---|---|---|---|
| $V_r$ . | 19·7 | 16·6 | 11·6 | 11·5 | 10·1 | 4·9 | 2·1 | 7·9 | 7·9 |
| $V_i$ . | 24·6 | 21·5 | 15·4 | 16·1 | 13·5 | 10·4 | 5·1 | 16 | 16 |

The probability of ionization taking place at a collision when it is energetically possible for it to occur increases rapidly above the ionization potential, and passes through a maximum at a potential which is very roughly of the order of a hundred volts, thereafter decreasing more slowly. In helium, collisions at about 180 volts are the most efficient, and some 22 per cent. result in the formation of a positive ion. It has been asserted that when the probability of ionization at a collision is plotted as a function of $V/V^i$, where V is the electron velocity in equivalent volts, a single curve represents the values for argon, helium, hydrogen and nitrogen within the limits of experimental error, up to a value of about 20 for $V/V_i$; but this result, as well as the numbers quoted for helium, depends upon still uncertain measurements of the distance an electron goes before making a collision in the different gases (§ 3). The probability of excitation taking place at a collision when the electron has sufficient energy is much smaller, and usually attains a maximum not more than a few volts above the excitation potential, thereafter decreasing more rapidly than in the corresponding case of ionization.

It is possible for an electron to attach itself to a neutral atom or molecule, to form a negative ion. Much less is known of these than of positive ions, but they are certainly of less frequent occurrence at low pressures than at high, and their possible existence in glow discharges is usually ignored.

It does not necessarily follow that an excited atomic system will emit radiation when it returns to the normal state. The energy available may be used to excite another system of lower excitation potential, any excess going to augment the relative translatory motion of the two reacting particles, being distributed between them so as to conserve momentum. A simple example of this is furnished by the so-called sensitized fluorescence of thallium vapour. Thallium emits a spectrum which includes a green line at 5350 A, but little or no trace of this can be found when thallium vapour is exposed to a strong source of mercury resonance radiation at 2537 A, since excitation of the thallium by radiation of this wave-length, although energetically possible, is a highly improbable event. A green fluorescence appears nevertheless at once if a little mercury vapour is allowed access to the thallium, since the mercury absorbs its own resonance radiation strongly, and can pass on the energy to thallium in collisions, giving a normal mercury atom, and an atom of thallium now in an excited state, and in a position to radiate. Processes of this type are of great importance in discharges, and the energy available may even serve to ionize the second atom or molecule, or to dissociate a polyatomic molecule. Such processes are often termed collisions of the second kind.

### 3. Mean Free Paths

The distances through which molecules move between collisions are distributed about a mean value $l$ in such a way that if a number of molecules are taken, each of which has just suffered a collision, and these are then re-examined after each has gone a distance L, a fraction $\varepsilon^{-L/l}$ will not have collided in the meantime, where $\varepsilon$

s the exponential constant. The value of $l$ depends to ome extent upon the definition of what is to be taken s a collision. The mean free path of a positive ion vould be expected to be a little less than that of a neutral article, since it will induce a negative charge on the roximate part of a neighbouring neutral molecule, which will tend to draw the two together. Some mean ree paths of neutral molecules, moving amongst molecules of a similar kind at a temperature of 0° C., and t a pressure of 1 mm. of mercury, are given in Table II.

TABLE II.

Mean Free Paths of neutral Molecules, in tenths of a mm. from Measurements of the Viscosity

| Gas . . . | $H_2$ | $O_2$ | $N_2$ | A | He | $H_2O$ |
|---|---|---|---|---|---|---|
| . . . | 1·20 | 0·68 | 0·64 | 0·67 | 1·89 | 0·41 |

On simple kinetic theory, electrons are effectively oints moving swiftly, and it follows that their mean ree paths in gases should be $4\sqrt{2}$ the mean free paths or the neutral molecules. This has been verified xperimentally in a number of gases so far as inelastic ollisions are concerned, for electrons with speeds between 0 volts and 200 volts, but the theory of the motion of n electron through a gas cannot properly be treated n purely kinetic grounds, as is shown by the abnormal ehaviour of slow electrons, especially in the inert gases. For velocities of the order of 4 volts, the mean free path s found experimentally to be much less than that alculated on kinetic theory from the constants for the eutral molecules, but it is very much larger than the inetic value, for still smaller speeds. The nature of he variation for xenon is shown in Fig. 5, where the eciprocal of $l$ for an electron is plotted against the quare root of its equivalent voltage, which will be proportional to its velocity (equation (2)). The corresponding curve for hydrogen, which is also shown, is nore nearly normal. The two horizontal lines give the inetic theory values, which are independent of the speeds

of the molecules, the upper line being that of xenon. There is evidence that some positive ions of the same speeds as the slow electrons have similar variations of the mean free path.

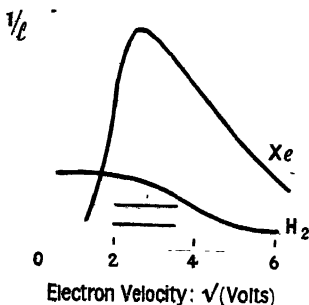



FIG. 5.—Mean Free Paths of Slow Electrons in Xenon and Hydrogen

## 4. OTHER FORMS OF DISCHARGE

The simple glow discharge is eminently suited for many electrical measurements, since it can be run steadily for considerable periods of time, particularly if a hot filament is used as cathode. Other forms are, however, often more suitable for other purposes, and some will be referred to again later.

The heavy current arc between metal or carbon poles is well known on account of its numerous technical applications. Its poles often become incandescent under the action of the discharge—although this is probably not essential for the maintenance of the arc—and can thus act as a powerful source of electrons; its colour is readily modified by feeding salts into it, a fact employed for the production of spectra. At low pressures a high current arc is very easily obtained if the cathode is kept incandescent by passing an auxiliary heating current through it, and under some circumstances can burn steadily when the applied voltage

is less than the lowest excitation potential of the gas (§ 18).

Discharges from points also present a number of interesting features. At low pressures they are obviously glows, but at atmospheric pressure a positive point has its tip covered with a velvety cap, whilst a negative point forms the apex of a cone of light proceeding out into the gas. Examination of the latter in helium with a microscope has shown that there are then two dark spaces present in the gas, separated by a thin bright layer; the various parts appear to be, proceeding out from the cathode, the cathode dark space, negative glow and Faraday dark space, and their presence indicates that the main effect of the increase

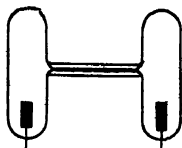



Fig. 6.—Simple Spectroscopic H-tube

in pressure is to concentrate the cathode parts of the glow discharge on to a small area of the surface of the negative electrode.

Numerous modifications of the cylindrical container of Fig. 1 have been made for spectroscopic purposes. One of the most useful is the H-tube shown in Fig. 6, in which two tubes of wide bore containing the electrodes are joined by a length of capillary tubing. The effect of the constriction is to produce a high-current density locally, with an accompanying great intrinsic luminosity of the discharge. The capillary may be viewed laterally, or end-on. If the tube is sealed up, small bulbs holding caustic potash and phosphorus pentoxide are often left attached, to absorb the carbon dioxide and water vapour respectively that are generated under the influence of the discharge when the tube

is running. Condensible vapours can be removed by keeping another attached tube immersed in a bath at the appropriate temperature, such as that of liquid air (−187° C.).

Occasionally tubes are provided with external electrodes and the current has to pass through the glass to the gas. A useful variation of this type of electrodeless discharge is one in which an E.M.F. is induced in the rarefied gas from a neighbouring high-frequency circuit, an action readily demonstrated by the lighting up of an insulated neon lamp if it is brought near the secondary terminals of an induction coil. The latter has proved valuable as a means of unravelling complex spectra, since different lines appear with varying intensities at different distances from the inducing circuit.

# CHAPTER II

## INITIATION OF THE DISCHARGE

### 5. Sparking Potentials

IT is still a matter of controversy exactly how a discharge starts, but a simple general picture of what happens can be obtained by supposing that a single electron starting from the cathode, which has been formed by a radioactive or other action, generates another $n$ electrons in its passage to the anode under the influence of the field. The corresponding number of positive ions arriving at the cathode will also be $n$, if the effect of lateral diffusion to the walls of the tube is neglected, and each of these can be supposed to excite the emission of another $f$ electrons from the cathode, where $f$ is a quantity less than unity. The discharge can then evidently maintain itself only if the product $fn$ is greater than unity. There is evidence that $f$ is independent of the pressure of the gas ($p$) and of the potential applied to the electrodes (V), but $n$ must depend on both of these factors, since the pressure determines the number of collisions made by an electron per centimetre of path, and the voltage, together with the geometry of the apparatus, and the pressure, determines the energy of an electron when it makes a collision. The sparking potential $V_s$ is therefore given by an equation of the form

$$\phi(V_s, p) = 1/f \quad . \quad . \quad . \quad . \quad (4)$$

The form of the relation between $V_s$ and $p$ has already been indicated (§ 1), and a typical experimental curve obtained near the minimum sparking potential is reproduced in Fig. 7.

The value of the sparking potential is greatly affected by even small changes in the composition of the gas, and cases have been recorded in which the presence of mercury vapour at a partial pressure of a hundredth of a millimetre of mercury has lowered it for an inert gas at several millimetres pressure by between 300 and 400 volts. The explanation of this is that a number of excited atoms of the inert gas are formed by the electrons in their paths towards the anode, and these excited atoms produce ionization of the mercury as a secondary process by a radiationless transfer of energy (§ 2). An

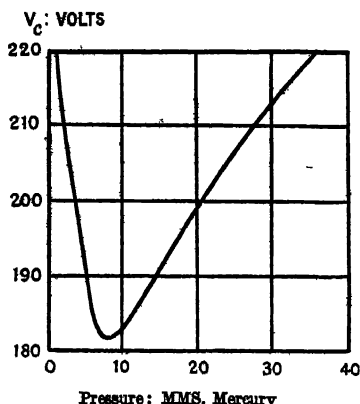



FIG. 7.— Sparking Curve for Helium with Electrode System of a small Technical Discharge Lamp.

excited atom of helium, for example, has an energy of 19·7 electron-volts, whereas only 10·4 electron-volts is required to ionize mercury. Any agents which remove the excited atoms in other ways will again tend to raise the sparking potential, and it is, in fact, found that exposure of the sparking-tube to a very strong source of radiation from the same inert gas has this effect, the active excited atoms being transformed by absorption of radiation into another excited form which has a much

horter life than the former before it returns to the ormal state spontaneously with emission of radiation, he chance of an impact of an excited atom with a nercury atom, with production of a new electron, being orrespondingly reduced.

Even when the applied potential is sufficient to start he discharge, an interval of time elapses before a self-naintained current starts to flow through the tube. The lag is very variable, and may be as small as a nillionth of a second, or as large as an hour. It is less, he greater the difference between the sparking potential and the applied potential. Several causes contribute o produce this effect. The most obvious one is that no discharge can pass until electrons are generated in ome way in the tube, and it is found that the lag is generally reduced by exposing the cathode to ultra-violet light of sufficiently high frequency to liberate photo-electrons from the metal, or by the presence in the vicinity of the tube of a radioactive source of gamma-rays, which acts similarly. This is not, however, the sole cause, and it seems that the phenomenon is closely connected with the condition of the surface of the cathode. If this is grossly dirty, or has been deliberately covered with a thin film of some poorly conducting substance, it has long been known that a small initial current will polarize its surface, and so produce a back E.M.F. similar to, but larger than, the back E.M.F. of an electrolytic cell. More recent work in which the cathode has been covered with a film of metallic sodium indicates that layers of gas at the surface of the metal have the same effect. The actual time taken for the discharge to build up to its maximum value is very small, and depends primarily on the time taken for an ion or electron to cross the tube from one electrode to the other.

### 6. Hysteresis and Oscillations

The passage of a self-maintained current changes the pre-existing electric fields in such a way as to make

ionization occur more frequently in the gas, which permits of a discharge, once started, being continued down to some lower potential ($V_b$) before it stops. This effect is referred to as hysteresis, and can be easily studied with the tube of Fig. 4, if the grid and anode are connected externally to form a single anode. Its characteristic curve—the graph showing the relation between tube current $i$, and applied voltage V—then takes the form shown diagrammatically in Fig. 8. With increasing voltage, the current at first increases regularly, but after a slight upward break at the ionization potential of the gas (A), suddenly increases largely at a point B and passes discontinuously on to an upper curve ECD.

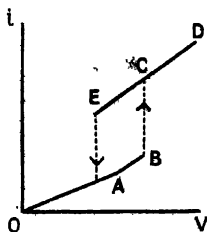



FIG. 8.—Characteristic Curve for Tube with a Hot Cathode

Once the new régime has been established, the characteristic can be followed down to a point E, corresponding to the voltage $V_b$, before the current falls discontinuously to a point on the initial line OAB. Hysteresis loops are of frequent occurrence in discharge tube characteristics. In the case of a discharge from a cold cathode, the line OAB coincides with the voltage axis, or is very little above it, whilst the rise on to the upper line occurs at a much higher applied potential than for a hot cathode. The two sections of the characteristic curve correspond to different distributions of space-charge in the tube (§ 11); for the upper line, the main fall of potential between the electrodes is concentrated much more closely on the cathode than for the lower line.

The existence of hysteresis makes it possible to generate oscillations by the aid of a discharge tube, which will be supposed for the present to have a cold cathode, using the circuit shown in Fig. 9. C is a capacity in parallel with the discharge tube D, and is in series with a battery of electromotive force E, and a resistance R. If C is initially discharged, and the circuit then closed by the key K, a charging current $(E - V)/R$ will flow into C through the resistance, where V is the instantaneous difference in potential between the plates of the condenser. As soon as the potential difference between the plates of C has reached the sparking potential

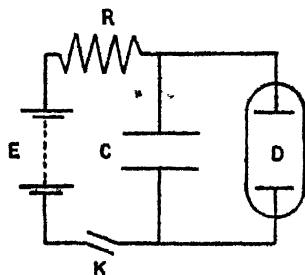



FIG. 9.—Circuit for Generating Capacity-resistance Oscillations

of the tube ($V_e$), if the lag is negligible a discharge will start, and will continue until the potential difference between the plates of C has fallen to the extinction voltage $V_b$ of the tube. The discharge will then stop, and the potential of C build up again until it reaches $V_e$, after which the cycle of discharge and recharge will be repeated. The current through the tube proceeds round the hysteresis loop once each cycle. If it is assumed that the time of discharge is small compared with the time required for recharging, it can easily be shown that the periodic time T of the oscillations is given by the formula

$$T = CR \cdot \log (E - V_b)/(E - V_e) \quad . \quad . \quad (5)$$

This formula can be verified only over a limited rang of conditions, as the phenomenon is complicated by a finite time being required for the discharge, by lag, an by other disturbing factors. By varying C, E and R it is, however, usually possible to obtain from a give tube a range of oscillations between radio-frequency and one discharge every half-minute or so.

Another type of oscillations frequently produced by discharge tubes has an audio or radio frequency, an is quite unaffected by the magnitude of the capacit or resistance, or by inserting an inductance in the circuit Little is known of these, except that their wave-form is sinusoidal, and that they are usually associated with a localized glow on the anode, but they are often a source of great trouble if it is desired to maintain a steady current through a tube. They appear to be due to some purely internal action, and are therefore usually spoken of as ionic oscillations. A tube with a hot filament can generate somewhat similar oscillations to the latter, of even shorter wave-length, down to a few centimetres.

### 7. The Complete Characteristic

The complete relation between current and voltage for a cold cathode tube containing gas at a pressure of a few millimetres of mercury is somewhat complicated, but in its main features follows the curve A–E of Fig. 10. On increasing the applied voltage from zero, and eliminating all but the very feeblest external ionizing agents, no current passes below the sparking potential $V_s$ (OA). If now the supply of power to the tube is limited by having a large resistance in series with it, increase of the current by decrease of this resistance is accompanied by a fall in the potential across the tube, and the curve ABC is realized, the currents being small, of the order of a microampere. The light in the tube is feeble, and near A is confined to the surface of the anode, but extends out towards the cathode, generally in the form of a bulb, in traversing BC. In neon, the whole of the

ace between the electrodes is occupied by striae under
ese circumstances, and it has been shown, in much
e same way as for the striae in mercury (§ 2) that the
fference in potential between successive pairs is about
·5 volts, the ionization potential of the gas. Proceed-
g from cathode to anode, the brightness of each
riation is almost double that of the preceding one,
om which it is concluded that when an electron ionizes
one luminous layer, both the parent electron and the
w electron which it has produced start off from rest,
d each of the pair repeats the process of ionization

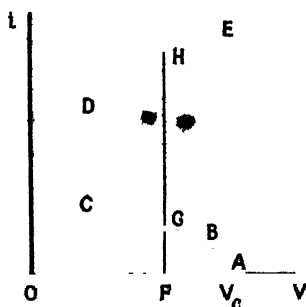



FIG. 10.—Complete Characteristic

the next luminous layer, when it has attained the
quisite energy. The path of an electron between
o striae is again tortuous because of the numerous
llisions that it makes with the neon atoms, and the
fect of the field is merely to superpose a drift velocity
on a species of thermal motion in which the effective
mperature of an electron at any point is measured by
e difference in potential between that point and the
eceding striation.

In the neighbourhood of C there is usually a discon-
uity in the discharge. The light concentrates itself
to a small space near the cathode; a glow discharge,
distinct from the previous Corona, appears, and if

striae were present before, the first of these becomes the cathode glow outside a primary dark space. In helium, other striae still persist farther out in the cathode dark space. Further increase in current leaves the voltage unaffected (CD), whilst the confined discharge spreads over the surface of the cathode, and the current density—total current, divided by the conducting area of the cathode—and thickness of the cathode dark space, remain almost constant. These conditions are referred to as 'normal', the current densities are of the order of a tenth of a milliampere per square centimetre, and the normal fall of potential is the lowest at which the discharge can be maintained. After the whole of the cathode is covered with glow (DE), conditions are said to become 'abnormal', and further increase in current can only take place at the expense of an increase in voltage, and a contraction of the cathode dark space.

Consideration of Fig. 9 enables us to extend and to make more precise the idea of a sparking potential, whose value will be seen to be largely a matter of definition. If, for example, the current FG is passing at voltage OF, and the external resistance is suddenly short-circuited, the corona changes into a glow, as the now unrestricted current passes to a point H on the upper curve, the voltage being held constant. OF is thus the sparking potential for a Threshold Current FG, and OA ($V_s$) is thus strictly speaking only the sparking potential for zero threshold current. Characteristic curves of the form of that shown in Fig. 10 are probably of general occurrence for cold electrodes. The curve between OAB and ECD, which should be present with a hot cathode (Fig. 8) and correspond to the threshold curve of Fig. 10, has not yet been investigated.

## CHAPTER III

## CATHODE PHENOMENA

### 8. The Alternative Path

THE path taken by a discharge in a tube is often somewhat unexpected, and not easy to account ɔr. One striking instance of this illustrates the fact, lready mentioned, that a discharge is extinguished 'hen the anode would be in the cathode dark space if current were passing. In the tube shown in Fig. 11 ıe pressure can be reduced, with the applied voltage eld constant, until the cathode dark space has expanded

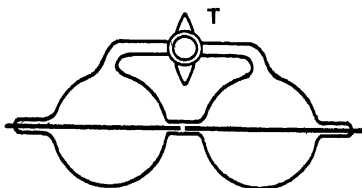



Fig. 11.—Alternative Path

p to the anode, and the discharge stops, the tap T eing meanwhile closed. On opening T, the discharge 'ill again pass, but it will now be seen to go round he alternative longer path which includes T, instead f immediately between the electrodes, since in this ıanner the cathode dark space can be developed on ıe negative electrode, but now proceeds inwards towards ıe centre of the corresponding large bulb.

### 9. The Primary Dark Space

The sections of the discharge near the negative elec- rode are shown with great distinctness in helium on

a cathode of potassium. The primary dark space (1) (Fig. 12) is well marked, and is bounded by a red rim (2), the cathode glow; the latter merges into a greenish cathode dark space (3), which in turn merges into a white negative glow (4). The discharge can be run at as low a potential as 100 volts. The primary dark space has hitherto been found only in the inert gases —helium, neon, argon, krypton and xenon—and in hydrogen. Its thickness (*d*) is rarely greater than a millimetre, and is approximately inversely proportional to the square root of the current density, thus varying with current in the same sense as the thickness (D) of the cathode dark space (§ 11). Unlike the latter, however,

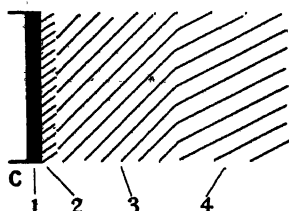



FIG. 12.—Negative End of Discharge through Helium

it is independent of the pressure of the gas. For any one gas $dV/D$ is constant, where V is the Cathode Fall in Potential, between the cathode and negative glow (Table III).

TABLE III.

Discharge through Helium at Pressures between 0·4 mm. and 3·0 mm.

| V Volts. | D cms. | *d* cms. | V*d*/D. |
|---|---|---|---|
| 204 | 0·381 | 0·039 | 20·9 |
| 271 | 0·562 | 0·048 | 20·3 |
| 325 | 1·010 | 0·064 | 20·5 |
| 420 | 1·472 | 0·072 | 20·4 |
| 590 | 1·422 | 0·047 | 19·5 |
| 770 | 3·168 | 0·090 | 21·8 |

It is usually supposed that the primary dark space owes its existence to an emission of electrons from the cathode, and that these do not have sufficient energy to produce a visible effect till they have fallen through a resonance potential of the gas. This explanation is not completely satisfactory, and in particular is inadequate to account for its failure to appear in discharges through oxygen and nitrogen. The primary dark space is very like a positive ion sheath (§ 16).

## 10. The Normal Discharge

The 'normal' régime, which corresponds to a cathode incompletely covered with glow (§ 7), is evidently of fundamental importance, and several empirical relations have been found to hold under these conditions, although it has not yet been possible to establish all of them theoretically. The experimental determinations of the cathode fall in potential also leave much to be desired. The earliest of these were made by finding electrostatically the difference in potential between the cathode and an insulated exploring wire inserted in the negative glow, which can give only approximate results, both because of the uncertainty attached to the use of a probe in this way (§ 15), and because of the existence of direct or reversed fields in the negative glow itself (§ 21). Such measurements are no more reliable than those obtained by taking the cathode fall to be the potential difference between the cathode and anode when the latter is in the negative glow. Systematic investigations by the accurate use of exploring electrodes (§ 16) are lacking, and the least unsatisfactory are probably those in which the cathode fall is taken to be the smallest difference in potential between the anode and cathode when the anode is brought towards the cathode through the negative glow.

The dependence of the normal cathode fall ($V_n$) upon the density of the gas has been studied carefully by the last method with a massive cathode of iron, a large electrode being used to keep the temperature of the gas

from rising unduly under the influence of the discharge. In oxygen and air, $V_n$ is independent of the pressure of the gas ($p$) within the limits of experimental error; some data for oxygen are given in Table IV.

TABLE IV.

Relation between $V_n$ in Volts, and $p$, in mms. Mercury, for Oxygen; Cathode of Iron

| $p$ | 3·77 | 2·83 | 2·22 | 1·24 | 0·81 | 0·26 | 0·10 |
|---|---|---|---|---|---|---|---|
| $V_n$ | 354 | 352 | 352 | 352 | 351 | 346 | 351 |

The change with pressure is also small for the inert gases. In helium $V_n$ rises by only 3 per cent. from 153 volts, when the pressure is lowered from 14 mm. to 0·6 mm., whilst in neon the rise is 7·5 per cent. from 151·5 volts, between 4·3 mm. and 0·5 mm., and in argon 6·6 per cent. from 162·6 volts, between 7·2 mm. and 0·3 mm. With hydrogen and nitrogen, on the contrary, there is considerable change, and for the former, although $V_n$ is indeed about 250 volts between 15 mm. and 2 mm. pressure, it rises to 318 volts at 0·4 mm., whilst for the latter gas, $V_n$ is about 162 volts between 24 mm. and 10 mm., and then rises to 262 volts at 0·05 mm.

Some other values of the normal cathode fall on a platinum electrode, in measuring which no account was taken of possible variations of this nature, are given in Table V. In general, $V_n$ is least for the inert gases.

TABLE V.

Normal Cathode Fall, in Volts; Electrode of Platinum

| Gas | $N_2$ | A | $H_2$ | He |
|---|---|---|---|---|
| $V_n$ | 232 | 162 | 300 | 165 |

When the normal cathode fall is not constant, it is obviously difficult to attempt to correlate its values with any constants of the material of the cathode. It is found nevertheless that $V_n$ increases with the work that has to be done to remove an electron from the surface of the latter. The attractive force against which this work must be performed can be regarded as due to

the positive charge induced by the electron on the surface it is leaving, and may be shown by the theory of electrical images to be equivalent to a potential difference of $e/4d$, where $e$ is the charge of the electron, and $d$ a distance of atomic dimensions ($10^{-8}$ cm.), different for every surface. This potential difference is referred to as the Work Function, and usually denoted by $\phi$. Some corresponding values of $\phi$ and $V_n$ for a discharge in air are given in Table VI, from which it will be seen that the two sets of numbers run parallel with one another.

TABLE VI.

Relation between Normal Cathode Fall (Volts), and Work Function (Volts); Discharge through Air

| Cathode | Mg | Al | Fe | Sn | Pt |
|---|---|---|---|---|---|
| $V_n$ | 247 | 302 | 363 | 393 | 425 |
| $\phi$ | 2·7 | 3·0 | 3·7 | 3·8 | 4·4 |

This relation is somewhat surprising, since $V_n$ is necessarily measured in a gas, and the values of $\phi$ used, which were obtained in a high vacuum, are known to be often markedly affected by the presence of gas.

Speaking generally, the normal cathode fall is least in the inert gases, and with electrodes that liberate electrons easily. Possibly too there is a constant value of $V_n$ for each gas and metal which is quite independent of pressure, so long as the cathode material is unaffected by the gas to different extents at different pressures ($\phi$ variable) and the gas itself is unchanged by pressure; polyatomic gases, for example, often dissociate to an extent which depends upon their density.

The normal current density ($i_n$) and the normal thickness of the cathode dark space ($D_n$), which are closely constant at each pressure, so long as the cathode is not completely covered with glow, do however vary definitely with pressure in all cases, and it has been found experimentally that both $pD_n$ and $i_n/p^2$ are approximately constant for any given gas and cathode material. The first of these is an example of the reciprocal relation between pressure and the linear dimensions of a section

of the discharge that is found to hold in numerous other instances. An example of the constancy of the latter expression is given in Table VII.

TABLE VII.

Discharge through Helium on a Platinum Cathode of 6·33 mm. Radius; $i_n$ in milliamps/cm.[2], $p$ in mms. Mercury

| | | | | |
|---|---|---|---|---|
| $p$ . . . . . . | 4·00 | 3·49 | 2·38 | 1·06 |
| $\sqrt{i_n}/p$ . . . . . | 0·097 | 0·104 | 0·103 | 0·125 |

Other empirical relations, of less importance than the last two, have also been found. This pair has been shown to be a consequence of a theory of the normal cathode fall space, which starts from the general principle that with a normal fall the distribution of electric field must be that most favourable for ionization by electrons, and so proceeds, essentially by a development of the ideas outlined in § 5, to establish relations between the ionization constants of the gas, and $V_n$, $p$, $i_n$ and $D_n$. $V_n$ is taken to be a known constant for each gas and cathode. This theory also predicts that for a given discharge gas, the product $pD_n$ should be nearly proportional to $V_n$, which is approximately the case (Table VIII).

TABLE VIII.

Relation between Discharge Constants; Cathodes of Aluminium and Iron.

| | $N_2$ | A | $H_2$ | He |
|---|---|---|---|---|
| $(pD_n)_{Fe}/(pD_n)_{Al}$ . . | 1·37 | 1·25 | 1·24 | 1·26 |
| $(V_n)_{Fe}/(V_n)_{Al}$ . . . | 1·16 | 1·32 | 1·30 | 1·33 |

## 11. THEORY OF THE CATHODE DARK SPACE

Before the theory of the cathode dark space can be considered in detail, it is necessary to grasp the physical meaning of an important electrostatic theorem due to

Poisson. Usually all the lines of force which start from the positive plate of a condenser end on the opposite negative plate; and if the system is plane-parallel, and so far as edge corrections are concerned, of infinite area, the electric field X between the two is uniform, and given by the expressions

$$X = -\frac{dV}{dx} = -\frac{V}{D} \quad . \quad . \quad . \quad . \quad (6)$$

D being the distance apart of the plates, and the axis of $x$ being supposed normal to them with its positive direction in the direction in which V increases. The state of affairs is shown in the upper part of Fig. 13. If, on the other hand, there are uncompensated positive charges

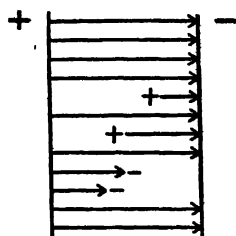
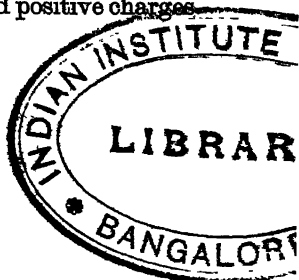



Fig. 13.—Space-charges

between the plates, lines of force from these will end on the negative plate, and the positive plate will be partially screened from the other. The lines of force run as in the middle section of the figure. If the space charge is negative the negative plate is screened from the positive one, and the lines of force run as in the lower part of the diagram. The density of the lines of force is thus not constant when there is either a positive or a negative space-charge, or, in other words, the electric field changes from point to point on a line perpendicular to the two plates. The mathematical formulation of this is that

$$\frac{d^2V}{dx^2} = -4\pi\varrho \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where $\rho$ is the quantity of positive electricity per unit volume. It follows that the simple linear fall of potential (OBP, Fig. 14), which occurs when there is no resultant space-charge, will be distorted to the form given by a curve such as OAP when there is a positive space-charge, and by a curve such as OCP when there is a negative space-charge.

The reason why the main fall in potential through a glow-discharge is concentrated near the cathode can now be appreciated. Suppose that to start with positive ions and electrons were uniformly distributed between an anode and cathode, so that their individual concentrations were equal at all points. The resultant space-

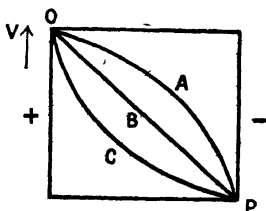



FIG. 14.—Effect of Space-charges on the Electric Field

charge would be everywhere zero, and the electric field the same as if no charged particles were present. Under the influence of the field the electrons move towards the anode and the positive ions towards the cathode. The electrons are, however, much lighter than the positive ions, and hence there is set up rapidly a positive space-charge in front of the cathode in which many of the lines of force terminating on the latter have their origin. In a glow-discharge there is a continual generation of new ions and electrons going on, but the effect is much the same, and the resulting region of positive space-charge against the cathode constitutes the cathode dark space. The difference between the corona-discharge (§ 7) and the glow-discharge is that in the former the concentration of positive ions is so small that the field

between the two electrodes is not appreciably disturbed, on the average, by their presence ; whilst in the latter it is so large that all the lines of force which terminate on the cathode have their origin on the positive charges in the cathode dark space, and none penetrate to it from the negative glow, or parts of the discharge to the positive side of the latter.

The exact nature of the processes of ionization which occur within the cathode dark space is still obscure, but there are certain points on which there is fairly general agreement. The existence of a minimum (normal) cathode fall in potential must be due to much the same causes as those which give rise to a sparking potential (§ 5). There is unquestionably too some emission of electrons from the cathode itself, which gives rise to the parallelism between $V_n$ and $\phi$ (§ 10) at normal cathode fall, and possibly to the primary dark space (§ 9). It is also difficult to see what other explanation could serve for the lowering of the cathode fall in potential which takes place when the cathode is made incandescent (§ 1), and is so in a state to emit electrons. Moreover, the cathode fall is decreased when the surface of the cathode is exposed to a strong source of ultra-violet light of sufficiently high frequency, or when it is bombarded with cathode rays from an auxiliary discharge, both of which set electrons free from the metal. When the discharge is running without external aid of this sort it is, however, not known certainly whether the emission from the cathode is due to bombardment by positive ions, to the action of radiation from the dark space, or to bombardment by electrons moving about in more or less random directions amongst the positive ions. Possibly all three processes come into play to some extent. However they are produced, these electrons are repelled from the neighbourhood of the cathode, and move across the dark space towards the negative glow, producing fresh ions and electrons by collision with the gas. Other ions are formed by the radiation in the dark space, and possibly some by

the positive ions moving in the opposite direction. The electrons are swept into the negative glow fairly rapidly, and leave the positive charge in the cathode dark space, which furnishes a current of positive ions to the cathode. For low cathode falls in potential, the electrons are removed too rapidly to affect the positive space-charge to any important extent; but under some conditions with strongly abnormal cathode fall, the space-charge at the immediate surface of the cathode is reversed in sign by them (§ 12). There is some evidence from conditions in the negative glow that when the cathode fall is not strongly abnormal, all the positive ions in the cathode dark space are actually

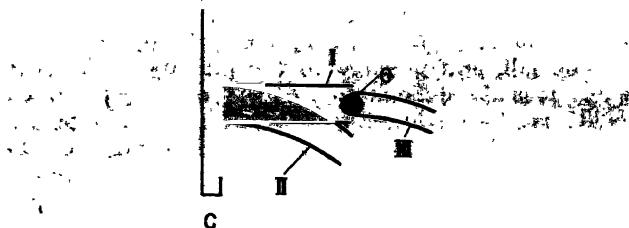



Fig. 15.—Shadows in Cathode Dark Space

formed within it, and few, if any, diffuse in from the negative glow. This is probably not completely true for a strongly abnormal cathode fall. In this case a clue as to the origin and mode of motion of the conducting particles is furnished by the shadows thrown by an obstacle such as a wire in the cathode dark space. These are especially instructive if obtained in a transverse magnetic field of such magnitude that it can alter the trajectories of electrons, without affecting those of positive ions appreciably. Three regions in which the already feeble light is further dimmed are then seen (Fig. 15). The first (I) is diffuse and passes perpendicularly from the cathode (C) to the object (O), showing that the obstruction is preventing positive ions from

eaching the cathode. The second (II) marks where lectrons which would have been liberated by these ositive ions are absent, whilst the third (III) marks hindering action of the obstacle on some other electron-roducing agent. Probably in this case some ions are lrawn from the negative glow, which may in turn be onnected with the fact that the boundary between the athode dark space and negative glow is usually much harper for abnormal falls than for normal falls, when, vith the inert gases in particular, it is often very diffuse.

To these uncertain points must be added two further lifficulties, viz. that the number of collisions made by he ions and electrons in traversing the dark space usually lies between ten and a hundred, which is too arge to be neglected, but too small to enable them to adapt themselves to the conditions obtaining in any one region before they are moved elsewhere, and that the kinetics of their motion under even simpler conditions are not yet properly understood. All things considered, it is not surprising that no completely satisfactory theory of the cathode fall space has yet been forthcoming.

All theories do agree, nevertheless, in predicting as a consequence of Poisson's relation, that as the potential difference between the cathode and the negative glow increases, the current must increase and the thickness of the dark space decrease, if the pressure is held constant, much as for positive ion sheaths (§ 16), and that the effect of an increase in pressure is to hinder the movement of the positive ions towards the cathode. If it is assumed that a positive ion has a drift velocity towards the cathode at any point which is proportional to the local field, and inversely proportional to the pressure (i.e. to the number of collisions made by the ion per centimetre of path), then, with certain simplifications of the theory, it can be shown that $iD^3P/V^2$ should be a constant for any one gas, which is found to be approximately true over certain ranges of conditions, for applied potentials up to about a kilovolt, and the

constant has much the same value for a number of gases. Somewhat better agreement with experiment is obtained by the use of two empirical formulae,

$$D = A/p + B/i^{\frac{1}{2}}$$

and

$$V = Fi^{\frac{1}{2}}/p + E$$

A, B, F and E are constants. These formulae are not satisfactory for the inert gases.

## 12. Electric Intensity in the Cathode Dark Space

The distribution of the electric field within the cathode dark space can be measured directly by two methods, excluding those which employ sounding electrodes,

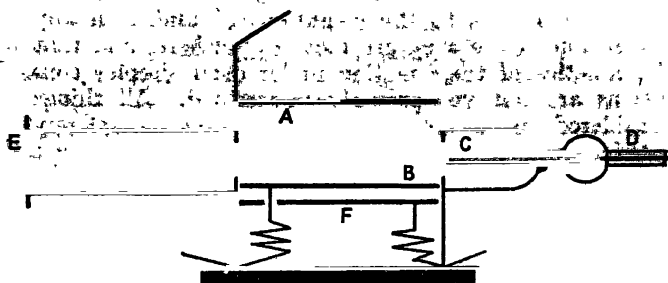



Fig. 16.—Apparatus for the Measurement of the Electric Field in the Cathode Dark Space

since their validity in this part of the discharge is highly questionable (§ 15).

In the first of these a beam of cathode rays from an auxiliary tube is shot transversely through the main discharge. The electrons in this beam are repelled from the cathode by the field in the dark space, and the electric intensity can be calculated from their deflection. One form of apparatus that has been used for this purpose is shown in Fig. 16. The main discharge passes between two discs of aluminium, 12 cm. in diameter

(A,B). The beam of electrons is introduced through the perforated anode of the discharge system CD, and the deflection of the beam is found from the position of the fluorescent spot of light which it excites on the Willemite screen (E). The system is calibrated by observing the deflection produced by known fields between the plates B and F, when there is no discharge passing between them. A, B and F are connected by a frame of glass rods, and are moved vertically by a winch which has not been shown. In this tube the main discharge is passed at from 300 volts to 1,000

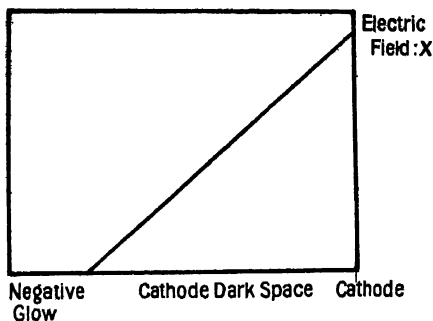



Fig. 17.—Field in Cathode Dark Space

volts, with a dark space about 3 cm. across, and the auxiliary tube is run at several kilovolts. Under these conditions it is found that the electric field X is closely proportional to the distance $x$ from the edge of the negative glow (Fig. 17), and since

$$V = -\int X dx \quad . \quad . \quad . \quad . \quad . \quad (8)$$

the negative potential at any point is proportional to the square of the distance from the edge of the negative glow. The total cathode fall in potential obtained by direct measurement agrees well with the value obtained from the field by equation (8). It is difficult to account

for this simple relation theoretically, but it has been shown that it would result if positive ions were being produced uniformly through the cathode dark space.

The positive ion density is, by equation (7),

$$\rho = -\frac{1}{4\pi}\frac{d^2V}{dx^2}$$

and is therefore constant across the dark space under these conditions. For a dark space 3 cm. thick, with a cathode fall in potential of 450 volts, $\rho$ has a value of 0·025 e.s.u. per c.c., which corresponds to $5\ 10^{7}$ singly charged ions. These numbers refer to a discharge through oxygen at a pressure of rather less than 0·1 mm. mercury, so that there was present in the dark space one excess positive ion for about every hundred million neutral molecules.

This method has not been used for the very low falls in potential that can be obtained with inert gases and alkali metal electrodes, and the simple relations found by its use cease to hold for applied potentials above about a thousand volts.

The second and more recent method is optical. Most spectral lines which appear single under ordinary dispersion are resolved into a number of components if their source is placed in a strong electric field. For example, the hydrogen line H$\gamma$ at 4341 A is separated into some 25 components, which are spaced almost symmetrically with respect to the undisplaced line, with a distance between the outer components of 13 A in a field of 30 kilovolts per cm. In this case, although not invariably, the separation of a component from the undisplaced line is proportional to the strength of the electric field. In narrow discharge tubes, with strongly abnormal cathode falls in potential, electric fields of this order occur, and this so-called Stark effect is present to a measurable extent. It is studied by throwing an image of the cathode dark space on to the slit of a spectrometer, so that the cathode (C) (Fig. 18) is at one end of the slit, and the negative glow (NG) at the

other. In place of the usual line (1) a pattern is now observed in the spectrum, built up of displaced lines such as (2). It follows from the shape of the displaced lines that under these conditions the electric field has a maximum at some distance, usually about a millimetre, from the cathode, and falls off both towards

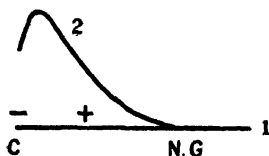



Fig. 18.—Stark Pattern

he cathode and the negative glow. By Poisson's quation there must be as many positive carriers as egative carriers at the maximum, a positive spaceharge between this and the negative glow, and a negaive space charge very close to the cathode. Observaion of these patterns provides a powerful method of pectrum analysis.

## 13. Radiation from the Cathode Dark Space

Most of the electrons that are generated in the cathode lark space make numerous collisions before they can nter the negative glow, at least when conditions are ot far from normal. If $l$ is the mean free path of an lectron, and $D$ again the thickness of the fall space, he fraction $\varepsilon^{-D/l}$ of the electrons that leave the cathode ill reach the negative glow without collision. At a ressure of a millimetre of mercury, $D/l$ is about 10 ith a dark space 5 mm. thick in argon, and the fraction qual to only about one-thousandth. At a pressure ten mes smaller, the fraction has risen to about one-third, nd the characteristic L radiation of argon, which quires for its excitation not less than 240 volts, can e detected from near the positive boundary of the

cathode dark space in a discharge through this gas at 400 volts, at the lower pressure.

The absence of much visible radiation from most of the cathode dark space is due to the relatively high speeds of the electrons and ions, and to their small concentrations. The increased luminosity in the cathode glow has not been studied in much detail, but is probably due both to an accumulation of positive ions and to excitation and ionization by the slow electrons from the cathode.

## 14. Heating of the Cathode

From the fact that the main fall in potential in a glow discharge occurs in the cathode dark space, it would be expected that most of the power supplied to the tube would be consumed in this region. This is found to be the case, and about 80 per cent. of the energy dissipated in the fall space is usually communicated to the cathode in the form of heat; this is actually rather more than would be expected from the thickness of the dark space. It has been shown that with certain glow discharges through hydrogen, practically the whole of the energy supplied to the tube is converted into heat, any other form of energy claiming less than 1 part in 200 of the whole.

# CHAPTER IV

# EXPLORING ELECTRODES

## 15. Insulated Probes

A METHOD that was at one time used extensively in attempts to find the potential in an ionized gas consisted in inserting a probe-wire, and then measuring, by a quadrant electrometer or similar instrument, the potential which it acquired. Results obtained in this way are inaccurate, for two reasons. First, the introduction of the wire disturbs the discharge, and secondly, it does not take up the potential of its surroundings. The first of these can be partly overcome by the use of a small length of very fine wire, but the other is of a fundamental nature.

In the uniform positive column of a glow-discharge, to take a definite example, where the electric field is small and practically constant along the tube, there are as many positive ions per unit volume as there are electrons, by Poisson's relation (equation (7)), the possible presence of negative molecular ions being ignored. If the electrons and positive ions were at the temperature of the gas, more of the former than of the latter would reach the 'collector' in a given time, if this were at the potential of the surrounding space, since an electron has a smaller mass and hence a greater average velocity than that of a positive ion at a given temperature. The condition of equilibrium for the collector, however, since it is insulated, is that its charge shall remain constant, i.e. as many positive ions as electrons must reach it per second, and so, in order to receive this zero 'ambipolar' current, it must take up a negative potential

relative to the surrounding space. The effect is exaggerated since both the electrons and the positive ions are subject to the action of the field in the positive column, and hence have a greater average energy than the neutral molecules, the corresponding temperature of the electrons, which may be specified by the relation,

$$3kT_e/2 = E_e \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where $E_e$ is their average energy, exceeding that of the positive ions because the light electron communicates less energy to a molecule on collision than does the massive positive ion. Measurements of potential with an insulated probe in the cathode dark space are subject to even greater uncertainty, since the positive ions have now also considerable energy.

An unambiguous measure of the local potential can be obtained if a hot wire is used. When this is positive with respect to the space, it cannot emit electrons; but if it is negative, the usual thermionic current can leave it. If then the potential of the wire is raised until the net electron current flowing from it into the gas—which will include positive ions and electrons received by it from the gas, with proper adjustment of sign—is the same whether it is hot or cold, it will be at the space potential. This method is of general applicability, provided the introduction of the probe does not affect the pre-existing discharge.

## 16. Cold Collectors

The exact analysis of what occurs when a cold collector is put in an ionized gas has led to important advances in the last few years. The essential features of this new work can be shown by consideration of the processes occurring at the surface of a flat collector. For the sake of definiteness, we will suppose that the ionized medium is mercury vapour, containing $n_p$ positive ions and $n_e$ electrons per c.c., the ions having a random Maxwellian distribution of velocities corresponding to a temperature $T_p$, and the electrons a temperature $T_e$, greater than $T_p$.

In some cases we can conveniently refer the average energy to equivalent volts V, by the relation

$$eV = 3kT/2 \quad . \quad . \quad . \quad . \quad . \quad (10)$$

or, substituting numerical values for the constants,

$$V = T/7730 \quad . \quad . \quad . \quad . \quad . \quad (11)$$

When the collector is made strongly negative, so that it repels effectively all the electrons directed towards it, but attracts the positive ions, it is observed that—

(*a*) The current of positive ions flowing to it is almost constant, if due allowance is made for edge effects.

(*b*) The collector is covered with an almost non-luminous sheath (Fig. 19), whose thickness increases with the difference in potential between the collector and the ionized gas. As is indicated in the figure, there is also

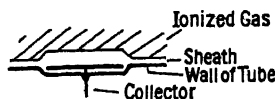



FIG. 19.—Positive Ion Sheath

a sheath on the walls of the tube ; the thickness of the latter sheath is independent of the potential of the collector.

The observation (*b*) indicates that the region of the lischarge disturbed by the collector (and the walls) is strictly limited, and (*a*) furnishes the key to the problem, n that the flow of ions to the collector is controlled by he space charge which they excite in its neighbourhood. The density of positive ions being attracted is so great hat all the lines of force which terminate on the col-ector have their other ends on positive charges in the lark sheath, which thus acts as an electrostatic shield o the remainder of the gas. The sheaths are similar to he cathode dark space in this respect, but differ from t in that the presence of the collector is not essential or the maintenance of the discharge, whereas that of the athode is. It has also been shown that there is no

secondary emission of electrons from a nickel collector in mercury vapour under the positive ion bombardment, although there is some such emission with other metals and other gases. The absence of light from the sheath is due to the same general causes as operate in the cathode dark space. The current to the collector is constant because the number of mercury ions which strike the outer edge of the sheath per second, and are then drawn inwards, depends only on conditions in the undisturbed main discharge, and so the only effect of increase in the potential of the collector is to include more positive ions in the accelerating field in a sheath of greater thickness. It follows from the kinetic theory of gases that the 'random' positive ion current ($i_p$) in the ionized gas, which is that passing though unit area in it from one side to the other, and is evidently the same as that striking unit area of the outer surface of the sheath per second, is given by the relations

$$i_p = \tfrac{1}{4}n_p e v_p = n_p e \sqrt{\frac{kT_p}{2\pi M}} \quad . \quad . \quad . \quad (12)$$

where M is the mass of a positive ion, and $v_p$ its average velocity of thermal agitation.

The mathematical formulation of these ideas for a plane collector is simple, if the effect of collisions made by the positive ions can be neglected, which will be the case if the pressure is sufficiently low. Let $\rho$ be the volume-density of positive electricity in the sheath at a point where the potential is $-V$, V being zero at the outer boundary where it abuts on the ionized gas. At this point a positive ion will have a speed $v$ towards the collector, where

$$\tfrac{1}{2}Mv^2 = eV \quad . \quad . \quad . \quad . \quad . \quad (13)$$

The current density $i_p'$ brought to the outer boundary of the sheath per second must be maintained throughout the sheath, since conditions do not change with time, and hence the space-charge at any point in the sheath will be given by

$$i_p = \rho v \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

Eliminating $\rho$ and $v$ between equations 7, 13 and 14, nd remembering that V measures the numerical value f the negative potential,

$$\frac{d^2V}{dx^2} = 2\pi i_p \sqrt{\frac{2M}{eV}} \quad . \quad . \quad . \quad . \quad (15)$$

Iultiplying both sides of this equation by $\frac{dV}{dx}$, and inte- rating, subject to the condition that $\frac{dV}{dx}$ and V are zero imultaneously, i.e. the influence of the collector does ıot extend beyond the outer boundary of the sheath,

$$\left(\frac{dV}{dx}\right)^2 = 8\pi i_p \sqrt{\frac{2MV}{e}} \quad . \quad . \quad . \quad (16)$$

ntegrating again, with $V = 0$ when $x = 0$, and solving or $i_p$,

$$i_p = \frac{\sqrt{2}}{9\pi} \sqrt{\frac{e}{M}} \frac{V^{3/2}}{D^2} \quad . \quad . \quad . \quad (17)$$

vhere D is the thickness of the sheath.

Inserting the appropriate numerical constants, with $i_p$ n amperes per sq. cm., V in volts and D in cms.,

$$i_p = 5{\cdot}45 \; 10^{-8} V^{3/2} D^{-2} M^{-\frac{1}{2}} \quad . \quad . \quad . \quad (18)$$

Chis equation must be corrected slightly to allow for the act that the positive ions have actually a small velocity f thermal agitation when they enter the sheath ; to do his, the right-hand side of the last equation must be nultiplied by the factor

$$1 + 0{\cdot}025 \; (T_p/V)^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad (19)$$

In properly constructed tubes the sheath thickness D) can be measured by a cathetometer, when it is ound that equation (17) is closely verified ; $i_p$ is found rom the current to the collector and its area. The bserved sheath thickness ($D_0$) agrees closely with that alculated by the aid of equations (18) and (19) ($D_c$), f due allowance is made for the effects at the edge of the ollector. An example of this is given in Table IX, the ube used containing mercury vapour at a temperature

of 13° C. and a pressure of 81 bars (a bar is 1 dyne per sq. cm., or very approximately a millionth of an atmosphere). The discharge was of the nature of an arc at 27·5 volts (§ 17), the tube current being 0·40 amp., and the random positive ion current ($i_p$) 0·119 milliamp. per sq. cm. The collector was situated in a spherical bulb 7·5 cm. in diameter: the potential of the positive column near the collector was 7 volts negative to the anode.

TABLE IX

| Potential of Collector. Volts, — *ve* to Anode. | Sheath Thickness; mms. Observed, $D_0$. | Calculated, $D_c$. |
|---|---|---|
| 400 | 5·24 | 5·27 |
| 300 | 4·12 | 4·24 |
| 80 | 1·54 | 1·57 |
| 50 | 1·05 | 1·08 |
| 30 | 0·77 | 0·70 |

As the potential of the collector is made less negative, and approaches that of the space, it is found that the net positive ion current received by it starts to fall off, and ultimately changes sign (Fig. 20). This is due to penetration of the sheath by an increasing number of electrons which have a sufficiently great normal component of velocity when they strike the sheath to carry them through the field retarding their motion to the collector. When the space potential is reached, the positive ion sheath, which has been continually decreasing in thickness, vanishes and the collector receives the currents of positive ions and electrons which would otherwise pass undisturbed across the corresponding area in the region outside the sheath, when the latter is present. The net current is negative, because, as already explained, the random electron current is much in excess of the random positive ion current. After passing the space-potential, the positive ion sheath is replaced by one of electrons, which increases in thickness according to equation (17), using now $m$, the electronic mass, and $i_e$ the random electron current, in place of M and $i_p$ respectively, and the current received is now the practically constant larger one that corresponds to

$i$, and the area of the collector. The temperature of the positive ions is so much less than that of the electrons that a small potential difference, of the order of a volt or less, prevents them from reaching the collector, but for the same reason no estimate can be made of $T_p$ by the method which will be described below, which gives $T_e$. At about 11 volts positive to the space a large increase in electron current often sets in, due to collapse of the negative space-charge as the electrons acquire sufficient energy in the accelerating field in the sheath to enable them to ionize mercury, and so generate slowly

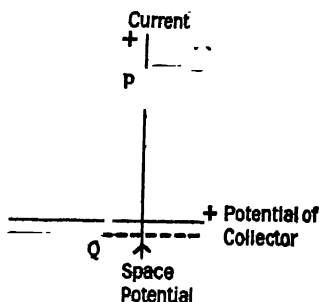



FIG. 20.—Diagram (not to scale) of the Characteristic Curve of a Flat Collector

A current above the voltage line (+) is one in which the collector is receiving more electrons than positive ions from the gas. A positive potential relative to that of the space corresponds to electrons being accelerated towards the collector.

moving positive ions which rapidly annul the negative space-charge due to the more swiftly moving electrons.

Analysis of the section PQ of the characteristic, where electrons are being received in quantity in a retarding field, enables us to find the space-potential, the temperature of the electrons, and their random current density and concentration. By a theorem in the kinetic theory of gases, due to Boltzmann, the concentrations of a system of particles at temperature T at two places where the difference in the potential energy of a particle is W, are in the ratio $\varepsilon^{-W/kT}$, the concentration being least

where the potential energy is greatest. In this particular case, if $V_e$ is the voltage equivalent to the temperature $T_e$ of the electrons, and V the retarding potential across the positive ion sheath, the ratio of the concentration of electrons at the surface of the collector to their concentration at the outer boundary of the sheath must therefore be $\varepsilon^{-3V/2V_e}$, and the corresponding current of electrons to the collector ($I_e$) the corresponding fraction of the random electron current in the ionized gas, or, by equation (12)

$$I_e = A\tfrac{1}{4}n_e e v_e \varepsilon^{-3V/2V_e} \quad . \quad . \quad . \quad . \quad (20)$$

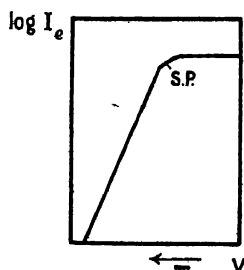



FIG. 21.—Semi-Logarithmic Plot of Electron Current in a Retarding Field

where A is the area of the collector. $n_e$, $V_e$ and $v_e$ are here constants, since they refer to conditions in the undisturbed discharge, and hence from equation (20),

$$\frac{d}{dV}(\log I_e) = -3/2V_e. \quad . \quad . \quad (21)$$

i.e. the logarithm of the difference between QP and the extrapolated positive ion current (– – –), should give a straight line when plotted against V. The form of plot obtained in this way is shown in Fig. 21, and gives information on three points.

(1) The distribution of velocities amongst the electrons is Maxwellian, since the relation is linear.

(2) The temperature $T_e$ ($V_e$) can be deduced from the

slope of the line, by equation (21). In the case of the collector referred to in connexion with Table IX, this was 29,100° abs., or 3·76 volts.

(3) The space potential can be taken to be that point (SP) to the right of which the linear relation ceases to be true, electrons being thereafter collected in an accelerating field. Usually secondary effects prevent a horizontal straight line being obtained immediately to the right of the space potential, as is indicated in the figure.

From the electron current at the space potential, the random electron current ($i_e$), and concentration of electrons ($n_e$) can now be found accurately by the use of equations (12) and (21). The floating potential of the collector, i.e. the potential it assumes when insulated, is evidently that corresponding to where the collector characteristic crosses the axis of voltage, and its value calculated from the random positive ion current, and, employing equation (18), the random electric current agrees well with that observed. The error inherent in the older method of using sounding electrodes (§ 15) can be found in this way, and although it depends upon the conditions in the discharge, may be as much as 5 volts, besides which, the new method gives a great deal of information which it was impossible to obtain before.

For any large collector covered with a thin sheath, the theory just given will apply in its entirety, since any effect of the curvature of the sheath can then be neglected. The use of a large collector is, however, often undesirable, either because the discharge conditions vary through the region which it is serving to analyse, or because it disturbs the main discharge by drawing too heavily upon its stock of ions and electrons. In such cases fine wires, or small balls, must be employed. The theory of their use does not differ essentially from that of a plane collector. The difference in potential between the collector and the main discharge is localized in a space-charge sheath of appropriate sign, across which the potential is controlled by Poisson's relation,

and the electron constants and the space-potential can be found exactly as before from the electron current in a retarding field, obtained by extrapolating the positive ion current for large collecting voltages to small collecting voltages, and assuming that the difference between the experimental and extrapolated lines is the electron current. The outer area of the sheath increases now with increase in voltage across the sheath, and the positive ion current behaves likewise. At the same time, not all the particles striking the outer boundary of the sheath and accelerated inwards will reach the collector, since some of them will describe orbits which

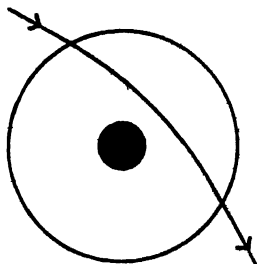



FIG. 22.—Orbit of Ion or Electron which does not intersect the Collector

do not intersect the collector, as is indicated in Fig. 22, where the outer circle represents the outer boundary of the sheath, and the inner circle the collector. It has been shown that by the appropriate choice of collectors, fresh estimates may be made of conditions in the discharge from those parts of the characteristics which correspond to reception of particles in accelerating fields. Another closely similar method makes use of the controlled flow of ions through an orifice in a charged plate.

## 17. MERCURY ARCS

The first important applications of these new methods were made to the study of arcs through mercury vapour,

which are important technically both for illuminating urposes, and as rectifiers for alternating current. A mall arc of this type, suitable for operation at between 00 volts and 250 volts, is shown in Fig. 23. The walls re of glass or quartz, and the electrodes are provided with xternal cooling fins. The tube contains a little liquid iercury in an otherwise evacuated space, and the arc s struck by tilting it to give a momentary connexion etween anode and cathode. The main localized fall f potential is again at the cathode, and the body of he tube is occupied by a brilliant positive column, which stands away from the walls, being in fact separ-ted from them by a sheath of positive ions, as with an

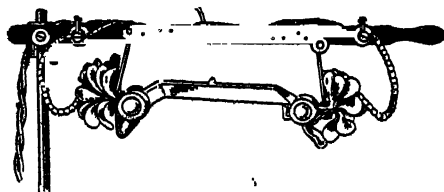



FIG. 23.—Mercury Arc Tube

nsulated probe. The fall of potential across the sheath s just adequate to maintain zero ambipolar current cross it, and the consequent re-combination of the ositive ions and electrons at the surface causes a con-iderable disengagement of heat.

A typical analysis for an essentially similar tube, 3 m. in diameter, carrying an arc of 2·0 amps. through iercury vapour at a pressure of 4·3 bars, showed that iere were 11·4 $10^{10}$ electrons per c.c. in the positive olumn, with a temperature of 23300° abs., giving a andom electron current density of 0·430 amps. per q. cm. The random positive ion current density was nly 1·17 milliamps. per sq. cm. The longitudinal otential gradient in the column was about half a volt er cm.

Some effects of pressure are shown in Table X, where the first column gives the pressure of mercury vapour in bars, the second the electron temperature, the third the ratio of the random electron current to the current density ($i_x$) in the main discharge between anode and cathode, i.e. to the tube current divided by the cross-section of the tube, and the last the ratio of the random electron current to the random positive ion current. The data were obtained by the use of cylindrical collectors.

TABLE X.

Effect of Pressure upon Conditions in the Positive Column of a Mercury Arc

| $p$ Bars. | $T_e$ Degrees Absolute. | $i_e/i_x$. | $i_e/i_p$. |
|---|---|---|---|
| 1·0 | 28,900 | 1·60 | 420 |
| 3·7 | 21,600 | 1·18 | 400 |
| 8·0 | 18,400 | 1·94 | 290 |
| 33·0 | 12,200 | 4·3 | 305 |

These results illustrate the main facts about conduction through the vapour under these conditions. The electrons carry by far the greater part of the random current, the relative contribution of the positive ions to this being, however, practically the same at the different pressures. The electron temperatures decrease as the density of the vapour increases, because of the more frequent collisions which they make with the mercury atoms; the electron temperatures are, however, found to be almost independent of the current carried by the tube, the chief effect of which is to increase their concentration proportionately. The total random current, the sum of $i_e$ and $i_p$, or what comes to almost the same thing, $i_e$ alone, is greater than the density of the current being taken through the tube from anode to

athode ($i_x$). This last fact is of great importance in onnexion with the mechanism of conduction through he ionized gas, the tube current $i_x$ being carried by the lifference in the random currents in opposite directions across a plane perpendicular to the axis of the tube. This point is brought out clearly in the theory of the node fall in potential (§ 22).

The fraction of the mercury atoms that are ionized ncreases almost proportionately with the current denity, other things being equal, and with the very high urrent densities that can be obtained with large currents n capillary tubes, almost complete ionization can occur, nd is accompanied by violent electrical surges. To uote a more usual case, in a discharge through mercury apour when there were $7{\cdot}3\ 10^{12}$ neutral atoms per c.c., he concentration of positive ions was $1{\cdot}8\ 10^{10}$ per c.c., iving a degree of ionization of 0·0025. For further nformation on the subjects of this section, reference must e made to the original papers (*see* Appendix).

### 18. The Abnormal Low Voltage Arc

It was mentioned in § 4 that arcs are readily maintained n gases at low pressure, if an incandescent filament s used as cathode. In helium, mercury and argon it is ossible to have the arc burning steadily, i.e. without scillations, at very low potentials, and in the case of rgon this has been effected at six volts, which is well elow the lowest excitation potential of the gas (Table ). Under such circumstances it is not at all obvious ow ionization of the gas can occur, although if the owest potential at which the arc could be maintained ad been the excitation potential the difficulty would ave disappeared, since ionization could take place by cumulative process, an atom being first excited, and hen ionized by a second collision with another electron efore it had an opportunity to return to its normal tate.

The paradox was removed by a direct application of he methods of analysis just described, a fine wire which

could be moved between the filament and anode serving as collector. It was found that in the immediate neighbourhood of the filament (F, Fig. 24), there was in argon a cathode fall in potential of about 11 volts, which is close to its excitation potential. Between this point and the anode (A) the electric field was, however, reversed. This now introduces a fresh difficulty, since in this part of the discharge the electrical forces will tend to move positive ions towards the anode, and electrons towards the cathode, i.e. tend to reverse the current. Solution of this follows in turn from the ob-

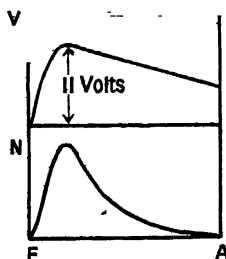



FIG. 24.—Potential Distribution (V) and Ionic Concentrations (N) in Low-voltage Arc

served variations in the concentrations of the electrons and ions (N, lower part of figure). These have a large maximum near the point of maximum potential, but fall off rapidly both towards anode and cathode. The concentration gradient is numerically the equivalent of an electromotive force, exactly as in an electrolytic concentration cell, and in the present instance its magnitude is approximately

$$E = \frac{kT_e}{e} \log \frac{N_1}{N_2} \quad . \quad . \quad . \quad . \quad . \quad (22)$$

where $N_1$ and $N_2$ are the electron concentrations at the points between which E is required. For example, the equivalent E.M.F. is about a volt if the concentration

of electrons at 10,000° abs. changes by a factor of two. In the present case, the diffusion due to a hundred-fold change in concentration served to carry a current of half an ampere through a reversed field of some 10 volts per cm. Concentration gradients of ions and electrons are of frequent occurrence in discharge tubes, and in calculating the total force acting on the charged particles, the E.M.F. equivalent to the forces of diffusion has to be reckoned in with the true electrical differences in potential.

## 19. Groups of Electrons

The conditions pictured in § 17, in which the electrons were supposed to have a thermal (Maxwellian) distribution of velocities, although ideal, are remarkably close to what is found in many cases when the gas-pressure

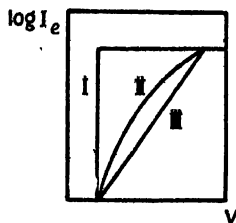



Fig. 25.—Semi-Logarithmic Electron Plots

is not too low, and the electric fields are small. Even under these conditions, however, deviations are often found, which may be grouped under two heads.

In the first type, the electrons present have a pronounced drift motion in some definite direction superposed on the random thermal motion. This shows itself by a semi-logarithmic retarded electron characteristic of form ii (Fig. 25), which lies between the purely thermal line iii and the line i which would obviously be obtained if all the electrons had a definite velocity in a definite direction. Curves of type ii are often obtained between

the luminous parts of the striae of the positive column of a glow discharge, whereas the simple type iii is obtained in the striae, indicating that the mechanism of the production of these is somewhat the same as that of the low current striae (§ 7).

In the second, the electrons can be analysed into a number of component groups, of which the slowest give straight semi-logarithmic plots, each corresponding to particles with a definite temperature. The reality of this effect has been established in the case of two groups in argon by an independent estimate of their average energies from the heating effect which they produced when they were received upon a spherical

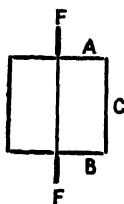



FIG. 26.—Simple Hot-filament System

molybdenum collector. It is usual to refer to the slowest group as 'ultimate', and the next slowest as 'secondary', but the distinction between them is somewhat arbitrary.

A great variety of groups can be obtained in a discharge at low pressures, of the order of 0·01 mm. mercury, from a hot filament (F, Fig. 26), to two circular discs (A,B), a cylinder (C) being used as collector. The potential difference between F and A (30–200 volts) is localized in a thin sheath of positive ions round the filament itself, the remainder of the gas being practically at the potential of the anode, and 'primary' electrons with energy corresponding to the full applied voltage pass out radially through the cathode sheath. Analysis of the characteristic curve of C shows—

(*a*) Primary electrons which have been collected without suffering any collisions with the molecules.

(*b*) Primary electrons that have made elastic collisions with the molecules.

(*c*) Primary electrons that have lost energy in exciting molecules.

(*d*) A high-speed group of electrons with a Maxwellian distribution of velocities, due largely to primary electrons that have made ionizing collisions, and to the electrons set free in these collisions.

(*e*) One or more slower groups with a Maxwellian distribution of velocities.

In one instance in the discharge through mercury vapour at a pressure of 102 bars (75° C.), with an applied potential of 100 volts, the group (*d*) was at 350,000°, and there were two slow groups (*e*) at 31,000° and 6,900° respectively. A great deal of information about the mechanism of electron collisions has been obtained by the use of these tubes. The slow ('ultimate') group is of very general occurrence in discharges, and is responsible for carrying the greater part of the current, and for neutralizing the positive space-charge of the positive ions present.

At higher current densities, the primary group (*a*) has often a distribution of velocities, and includes electrons with an energy greater than could be obtained directly in any of the electric fields present. The process responsible for the formation of the latter has not yet been established with certainty, but it may be connected with ionic oscillations.

# CHAPTER V

# THE NEGATIVE GLOW, FARADAY DARK SPACE, AND ANODE GLOW

## 20. The Negative Glow and Neighbouring Parts of the Discharge

THE contour of the negative glow follows that of the cathode fairly closely, but if for any reason the current density is greater at one part of the electrode than at another, the negative glow is farther off where the current density is less (§ 11). This occurs with tubes of the simple cylindrical form shown in Fig. 1. The discharge is concentrated somewhat towards the axis of the tube, because of the ambipolar current taken by the walls, and the negative glow can be seen to be nearer the cathode at the axis of the tube than at the periphery, particularly with small currents. The negative glow is also brightest opposite bright parts of the cathode glow, as would be expected from the close connection between the two which is required by the theory of the cathode darks pace (§ 11). The negative glow is always diffuse on its positive side, and fades away gradually into the Faraday dark space. It is also often difficult to localize any sharp boundary on its negative face, where it passes into the cathode dark space; but in some gases, and particularly in oxygen, this edge appears very sharply, and its position can be found to within a tenth of a millimetre. When the cathode is incandescent, or is made to emit electrons by other means, the negative glow closes in upon it, without marked change in intensity if the tube current is held constant. The maximum of intensity of the visible

diation from the negative glow is usually close to its gative face. The integrated visual effect of this diation, and of that from the cathode dark space and thode glow, is such as to give each part of this section the discharge a definite colour for each gas used, amples of which are given in Table XI. These colours e, however, very susceptible to the presence of impuri-es, some of the earlier investigators of helium, for ample, having recorded its negative glow as green, hereas it is now known to be white, and the colour of e negative glow also depends to some extent upon the rrent density.

TABLE XI.

lours of the Negative End of a Glow Discharge in Various Gases

| Gas. | Cathode Glow. | Cathode Dark Space. | Negative Glow. |
|---|---|---|---|
| Air . . . | Red | Violet | Blue |
| Oxygen . | Red | Violet | Yellow-green |
| Nitrogen . | Red | Violet | Blue |
| Argon . . | Red | Violet | Bluish-white |
| Neon . . | Yellow | Red | Orange |
| Helium . | Red | Dark green | White |
| Ammonia . | Blue | — | Yellow-green |
| Mercury . | Green | — | Green |

A more detailed spectrophotometric study of the gative glow has brought to light a number of unex-cted facts, of which the most significant is that even iere there is apparently a sharp boundary between e negative glow and cathode dark space, as judged sually, individual spectral lines undergo a much more adual transition. This effect can often be seen by oking at the negative end of a discharge through asses of various colours, when the apparent thickness the cathode dark space will be seen to vary. The ge recorded visually without the aid of light-filters

depends upon the observer, being the psychological interpretation of a physiological effect on the eyes, but it is usually found to be about where the total light intensity varies most rapidly with distance from the cathode, and to be somewhere more than half the distance from the cathode to where the light in the negative glow attains its maximum intensity. Relations which involve the thickness of the cathode dark space are correspondingly indefinite, and an electrical definition of this, based upon the fields present, would be preferable to the optical estimate.

In general, it is found that the greater the energy required for the excitation of any particular spectral line, the nearer does its maximum of intensity lie towards the cathode, and the less sharp is the maximum. The form of the intensity-distance curves is nevertheless not at all simple. A typical pair is shown in Fig. 27, which refers to a discharge through hydrogen containing a small quantity of mercury vapour. The upper curve is for the Balmer line H$\gamma$ of atomic hydrogen, and has a double maximum, the larger flat one being in the negative glow, and the smaller one against the cathode in the cathode glow. In the lower curve, which is that of the mercury line at 4047 A, there is no second maximum. It is usually found that when hydrogen is present as an impurity in other gases, the Balmer lines appear strongly in the cathode glow, whereas the mercury lines tend to come up nearer the anode, and often constitute the brightest components of the light from the anode glow. In Fig. 27, the line below the distance axis shows the position of the boundary of the cathode dark space, as judged visually, other spectral lines than those mentioned being, of course, present. In mixtures of gases, the separation of the maxima of different lines may be so pronounced that there appear to be two negative glows of different colours.

In addition to the spectra of the gas in the tube, lines due to neutral and ionized atoms of the material of the cathode often appear in the cathode dark space and

negative glow, whilst with very powerful discharges silicon lines from the silica and silicates of the walls may also be present. At the same time a deposit of the cathode metal forms on the walls, and shortens the useful life of the tube considerably. This effect is due to a disintegration of the cathode under the influence of the positive ions received by it from the cathode dark space, and is known as 'sputtering'. It is accompanied by an occlusion of gas by the sputtered film, which will lead to contamination of an initially gas-free electrode, since some of the sputtering material is redeposited there. The sputtering is not a thermal evaporation

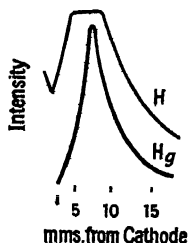



FIG. 27.—Spectrophotometric Analysis of Negative End of Glow Discharge

due to heating of the cathode, since it is almost independent of the temperature of the latter, provided it would not volatilize appreciably in absence of a discharge. The particles coming off have been shown to be at first neutral atoms, although they may acquire charges subsequently. The action can sometimes be traced to the temporary formation of chemical compounds of the cathode material and gas, but it is essentially due to a transfer of energy to atoms in the cathode by the direct impact of positive ions. The rate of sputtering increases with the current density, and with the cathode fall in potential, and in general, as might be expected in a collision process, with the molecular weight of the positive ions. Hydrogen is an exception

to the last rule, and gives rise to an abnormally large sputtering. Even under favourable conditions the amount of sputtered material, however, is small, and of the order of 0·05 gm. per ampere hour at 1000 volts. There is no simple relation between the amount of sputtering and the nature of the cathode, but some metals are more readily disintegrated than others, and it is possible to range them roughly in a list such as the following, in which any metal sputters less readily than its right-hand neighbour.

Mg, Al, W, Fe, Ni, Pt, Cu, Ag.

Hot filaments have a relatively short life when used as cathodes, as they disintegrate under the positive ion bombardment, and burn out.

An effect closely allied to sputtering is the disappearance or liberation of gas in the discharge. The disappearance is partly chemical, partly mechanical—a trapping of gas by the sputtering material as it deposits on the walls and electrodes—and partly due to the indefinite group of surface phenomena which are referred to collectively as 'adsorption'. Gas which is liberated comes from the electrodes and walls, and usually contains hydrogen and carbon compounds; its amount may be reduced by preliminary chemical and thermal treatment of the materials employed. The inert gases are the least absorbed during a discharge, and this fact is made use of in their purification, a heavy discharge being passed through them with electrodes of a chemically active material, such as potassium, or the liquid alloy of potassium and sodium.

## 21. Electrical Conditions in the Negative Glow and Faraday Dark Space

These parts of the discharge have been investigated in several gases by the accurate method of exploring electrodes (Chap. IV), using both cold and hot cathodes. The concentration of electrons and ions in the brightest part of the negative glow is greater than anywhere

else in a glow discharge, and may be as high as $10^{11}$ per c.c. It is from ten to a hundred times the concentration in the positive column. This maximum concentration falls off rapidly both towards the anode and the cathode, thereby giving rise to diffusion forces, just as in the low-voltage arc (§ 18). The electric fields in the Faraday dark space are always found to be small, and are frequently reversed at low pressures—e.g. at 0·3 mm. mercury in the discharge from a cold cathode through argon, with a current density of 0·5 milliamp. per sq. cm.—but it has been shown that under these conditions the concentration gradient is ample to effect the necessary transport of electrons from the negative glow to the anode. In the negative glow there are frequently two groups of slow electrons present, but these tend to merge into a single group in the Faraday dark space. If there is a positive column present, the temperature of the electrons rises as its head is approached through the Faraday dark space, and the direct electric field increases, preparatory to the new burst of ionization. There is some evidence that a fast group of electrons, with an average energy which is of the order of the ionization potential of the gas, is formed in the negative side of the negative glow from a partly directed stream of electrons entering it from the cathode dark space. With a cold cathode, the electric field is frequently reversed between the maximum of concentration in the negative glow, and the positive boundary of the cathode dark space.

The existence of any distinction at all between the negative glow and cathode dark space, even although optical investigations have shown that it is at the best indefinite, must be due to the fact that there is only a finite region which the positive ions in the cathode dark space allow to be affected by the negative charge on the surface of the cathode. There can also be little doubt that the ions in the negative glow have been produced directly or indirectly by electrons which have entered it from the cathode dark space, although very

little is known concerning these. For strongly abnormal cathode falls some have an energy corresponding to almost the full cathode fall in potential—cathode rays —but they are unlikely to be the only agent responsible for the formation of the negative glow, since they penetrate much farther into the discharge. Under more nearly 'normal' conditions it has yet to be shown that they are present, and probably the bulk of the ionization is produced by relatively slow electrons coming from adjacent parts of the cathode dark space into the smaller electric fields of the negative glow, where they will describe very tortuous paths, and so stand a good chance of making ionizing collisions in a short distance along the axis of the tube. Under approximately normal conditions it is probably these electrons which transport the main current between the cathode dark space and negative glow, a flow of positive ions in the opposite direction being hindered by the reversal of the field, whilst the current is carried from the negative glow into the Faraday dark space largely by diffusion of slow electrons in the concentration gradient. The adjacent parts of the Faraday dark space are really a part of the negative glow, the smaller luminosity of the discharge being largely due to the smaller concentration of the electrons and ions.

This picture of the processes coming into play also accounts in a general way for the spectrophotometric observations, especially as the electron temperatures are greatest at the cathode boundary of the negative glow, and fall off on passing through it into the Faraday dark space. It does not, however, decide if the excited atoms and molecules responsible for the emission of the radiation have been formed by recombination of ions and electrons, or by direct excitation of the neutral particles. On the one hand, the disparity between the intrinsic luminosity of the negative glow and that of the positive column is far less than the disparity between the concentration of ions and electrons in the two, so that it might be concluded that the light must arise

mainly from direct excitation. On the other hand, the spectrum of the negative glow, in helium, includes some continuous spectra that are characteristic of recombining ions and electrons. Evidently both processes are involved to some extent, but probably direct excitation is the more important.

### 22. The Anode Fall in Potential

The anode fall in potential has been studied systematically by the accurate method of exploring electrodes in mercury arcs, and in the glow-discharge through neon. The anode phenomena differ essentially from the cathode phenomena in that no one particular form is necessary for maintenance of the discharge, the one actually occurring in any particular instance being determined by the electric conditions in the positive column, or, if this is absent, in the Faraday dark space or negative glow. The large direct anode falls in potential, of the order of hundreds of volts, which are found when the discharge is very constricted in front of the anode, must obviously be excepted, since they are present to maintain the high degree of local ionization needed for the current to pass at all. In neon, three distinct types of discharge occur. An anode glow may be absent, or one may be present as a yellow sheet on the anode, or as a red hemisphere with its base on the surface of the electrode. In the first case, there is zero anode fall in potential, and in the second there is a direct anode fall in potential of 20 volts, which is close to the ionization potential of neon (Table I). These results, obtained first with exploring electrodes, have been confirmed by measuring the rate at which heat was generated at the anode, which is equal to $i\ (\phi + A)$, where $i$ is the current, A the anode fall in potential and $\phi$ the work function of the anode material for electrons (§ 10). The thermal measurements also showed that there was a direct anode fall of potential of rather more than the ionization potential in the third type of discharge. In mercury arcs, the anode fall in potential is positive or

negative according to circumstances. These effects can be accounted for in terms of the relation between the random current in the ionized gas immediately outside the anode, and the current entering the tube from the external circuit at the anode. For if the anode were at the same potential as the gas, it would draw from the latter a current $i_e A$, where $i_e$ is the random electron current (§ 17), and A the area of the anode, and only in exceptional circumstances would this be the same as the main current ($i_t$). If $i_e A$ were greater than $i_t$, the anode would have to charge up negatively so as to repel all but a fraction $f$ of the electrons directed towards it from the gas, where

$$f\, i_e A = i_t$$

and a negative anode fall in potential would result. The small contribution of the positive ions to the random current can usually be ignored. On the other hand, if $i_t$ were greater than $i_e A$, the anode would have to draw more current from the gas than if it were at the space potential. This calls for a direct anode fall in potential, which produces upon the anode a sheath of electrons which will act in one of two ways. If the area of the anode is less than the area of cross-section of the tube, the outer area of the sheath exceeds that of the anode, and since the current received by the anode, like that to any other collector, depends upon the rate at which charged particles diffuse from the main discharge to the outer boundary of the sheath upon it, the requisite increase in current between the anode and ionized gas is obtained. If, however, the anode occupies the whole cross-section of the tube, formation of a flat sheath upon it cannot alter the current received in this way, since the outer area of the sheath is identical with that of the anode itself; but if the fall in potential in the sheath is greater than the ionization potential of the gas, the negative space charge will collapse as the electrons passing through produce new ions, and the increase in current is obtained by the outward flow of the positive

ions and the inward flow of the new electrons. The outer boundary of the region which would have been occupied by the sheath on the anode now takes the place of the anode surface, and acts as an effective anode for the external ionized gas. Probably the yellow glow in neon acts in this way, and the red glow by increasing the effective area on the anode in addition. Very similar actions take place with a sudden change in the cross-section of a discharge tube, e.g., when a discharge has to pass suddenly from a tube of wide bore into a capillary.

# CHAPTER VI

# THE POSITIVE COLUMN OF GLOW DISCHARGES

## 23. The Uniform Column

THE positive column occupies those parts of the tube which are left vacant by the negative sections of the discharge and by the anode glow. It is bounded at its negative end by the Faraday dark space, and it may be either uniform or striated. It is separated from the walls by a positive ion sheath, across which there is a fall in potential that suffices to maintain a net zero ambipolar current of ions and electrons between the ionized gas and the insulated walls. In the case of a striated column, where conditions vary between striations, the sheath on the walls suffers concomitant changes. In some cases there is a dark space between the anode glow and a uniform positive column.

In a pure monatomic gas, striations occur only over a very limited range of pressures and current densities. With increasing contamination with other gases, the striae become more evident, and it is therefore not quite certain if they can be obtained at all with absolutely pure inert gases. In polyatomic gases they are easier to produce, but again the range of conditions under which they can be formed is the more restricted, the greater the degree of purity. The appearance presented by striae is very variable and often complicated.

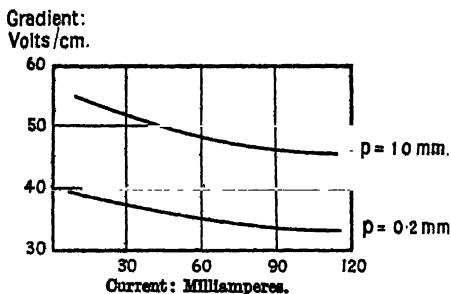
When striae are absent, the positive column may be either obviously luminous, or apparently non-luminous, according to circumstances. In wide tubes, several centimetres or more in diameter, the column is usually

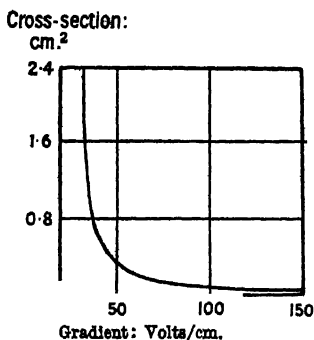
invisible, except in some electro-negative gases, such as water vapour. Provided the current is not too great, the longitudinal potential gradient (G) then depends almost entirely upon the pressure and nature of the gas; and in the case of very wide tubes, where the effect of the walls is negligible, G is approximately proportional to the pressure, being some 0·5 volts per cm. at a pressure of 1 mm. in neon, about 3 volts per cm. in nitrogen, and about 50 volts per cm. in water-vapour. In narrow tubes, the column is more usually luminous, but its intrinsic brightness depends upon the pressure, passing through a maximum as the latter is increased. Its colour is, as usual, very strongly affected by impurities, and, in addition, by the current density, the column changing from a red to a blue as the current is increased in argon, and from blue to white in nitrogen. When mercury vapour is present as an impurity, its spectrum appears with particular prominence at the anode end of the positive column, and especially in the anode glow, if the latter is present.

The electric fields in narrow tubes, unlike those in larger containing vessels, depend upon the current density and the diameter of the tube, as well as upon the nature and pressure of the gas. This is due mainly to the presence of the insulating walls, which now disturb practically the whole of the ionized column when they draw the zero ambipolar current from it, instead of merely affecting the periphery, as in wide tubes. The concavity of the striae towards the anode in a non-uniform column indicates that the wall, or, more strictly speaking, the inner (discharge) boundary of the positive ion sheath on the wall, is negative with respect to the axis of the tube, and the analogous radial potential gradient is in fact also present in a uniform column. This difference in potential, generally of the order of a volt in the latter case, has its origin in the decrease in current density which occurs in passing away from the axis of the tube, which is due mainly to a falling off in the electron concentration, with the

production of a corresponding E.M.F. of diffusion (§ 18). The longitudinal potential gradient can be found with precision from the difference in potential between two insulated exploring electrodes set similarly in the tube at a definite distance apart, since the difference in potential between the sound and the space will be the same in each case. Many measurements have been made in this way, and have been used in the study of how the potential gradient depends upon the nature of the gas, its pressure, the average current density for the whole cross-section of the tube, and the radius of the tube.

It is appropriate at this stage to point out that the use of the pressure as a variable to express discharge conditions is not exact. The pressure depends both upon the density of the gas and upon its temperature. The temperature of the gas-molecules is under most circumstances far below that at which any appreciable amount of ionization can take place in their mutual impacts, and hence the density alone, rather than the pressure, is the relevant variable, and should be deduced from the pressure and the temperature. It is, however, extremely difficult to estimate the latter. The introduction of any material thermometer both disturbs the discharge, and gives fallacious readings because of the heat disengaged in the recombination of ions and electrons upon its surface, whilst optical methods based on the Doppler broadening of spectral lines by thermal motion are also uncertain because broadening can occur for other reasons, and, in addition, at pressures low enough for the mean free paths of the gas-molecules to be comparable with the linear dimensions of the discharge vessel and connecting tubes to the pressure gauges, fresh complications arise from the phenomenon of thermal diffusion, if different parts of the apparatus are at different temperatures. It is therefore still usual to adopt the convenient but inaccurate course of specifying density by means of the pressure recorded by a McLeod gauge or other manometer attached to the

lischarge tube, and occasionally to supplement this ›y an estimate of the gas-temperature based upon

IG. 28.—Relation between Longitudinal Field and Current for Discharge through Nitrogen in a tube 1 cm. in radius

ıe rate of supply of energy to the tube, or based upon ıe temperature of the electrodes or walls.

IG. 29.—Relation between Longitudinal Field and cross-section of tube. Current of 0·26 amps./cm.² through Nitrogen at a Pressure of 8 mm. Hg

The general nature of the variation of the longitudinal ›ctric field (G) with current density ($i$), and with the ›ss-section of a cylindrical tube will be seen from e examples shown in Figs. 28 and 29. A current of

given density is passed more readily by a wide tube than by a narrow one, and the longitudinal field falls off as the current is increased. The general effect of an increase in pressure is to increase the longitudinal gradient required to pass current at a specified density, but in capillary tubes, at least, the fields tend asymptotically to constant values as the pressure is increased (Fig. 30).

The way in which the gradient depends upon the nature of the gas is not known definitely, but it may

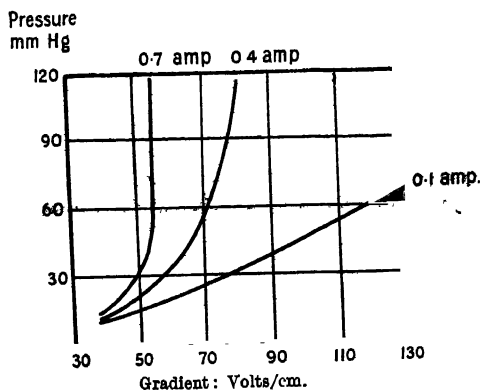



FIG. 30.—Relation between Longitudinal Field and Gas-pressure in a discharge through Nitrogen in a tube of 0·06 cm.[2] in cross-section. The numbers against the curves give the currents passing

be said generally that the discharge passes more readily through the inert gases than through nitrogen and hydrogen, whilst still higher forces are required in media such as chlorine and the vapour of mercuric chloride. These results cannot be referred completely to the number of atoms in the gas-molecules, or to any other simple property of the gas, since, for example, some investigators have found that oxygen conducts little worse than the inert gases.

The current passing through the positive column i

determined by conditions in other parts of the tube and in the external circuit, as well as by those in the column, and the electric field in the column has to be sufficient to pass this current under the conditions obtaining locally. From the spectrum of the positive column it is known that little recombination of positive ions and electrons occurs within it, so that the main function of the longitudinal field is to generate new ions and electrons at the rate at which they disappear towards anode and cathode, and diffuse to the walls. On this basis, with the additional well-founded assumption that the positive and negative space-charges are equal and opposite at all points, it has been found possible to give a theory of the uniform column in which the electrical and diffusion forces acting on each charged particle are included in a single equation of motion. In the special case now under consideration, where the mobility of the positive ions is negligibly small compared with that of the electrons, and the positive ions have a much lower random energy than the electrons, it has been shown that the longitudinal gradient (G) should be inversely proportional to the radius of the tube ($r$), and directly proportional to the average random speed of the electrons and to the square root of the ionization potential of the gas. The relation between G and $r$ has been verified experimentally, but too little is known of the other factors to say more than that as far as they are concerned, theory and experiment are in fair qualitative accord.

## 24. The Striated Column

Striations can occur in tubes of any shape, but even with cylindrical tubes they assume a variety of forms determined by the diameter of the tube and the conditions of discharge. Some of the forms which have been seen in hydrogen are shown in Fig. 31; their colour is red, white or blue, and often varies within a striation. In a tube of fixed diameter, the regions of pressure (D) and of current ($i$) within which particular

forms of striation are obtained can often be shown on a diagram such as that of Fig. 32. The striations are usually very diffuse when the discharge is oscillatory, but diffuse striae can be obtained with a steady discharge.

Fig. 31.—Some Types of Striations

The individual striae are usually concave towards the anode, and diffuse at the positive boundary, but sharp at the negative boundary. The maximum of intensity of the total radiation from a striation, as estimated by

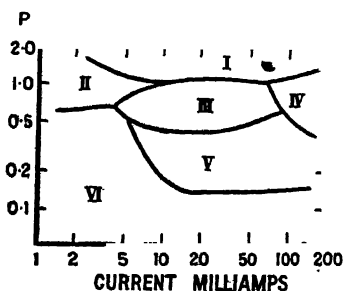



Fig. 32.—Striations in Hydrogen

P is approximately the Gas-pressure multiplied by one-third of the diameter of the tube in cms.

I Unstriated Column
II Diffuse Plate-like Striae
III Plates with a tendency to split into Double Striae
IV Pointed Plate-like Striae
V Thick Striae
VI Diffuse Thick Striae

the eye, occurs close to its negative boundary, but the spatial distribution of intensity varies throughout the spectrum. In general, lines which require little energy for their excitation appear first close to the negative boundary of a striation, which is the converse of what

is observed in the negative glow, but in both cases the maximum is sharper for lines which require little energy for their excitation than for those which require relatively large energy. The distance (S) between striae of any specified type is very approximately independent of the current, if this is large, but usually increases with decrease in pressure, and with increase in the diameter of the tube (2R). Employing the mean free path ($l$) of an electron of medium speed as variable instead of the pressure, it has been found that over considerable ranges of conditions a formula of the type

$$S = c(l/R)^m \quad . \quad . \quad . \quad . \quad . \quad (23)$$

expresses quite well the variations in the spacing of striae, $c$ and $m$ being constants for a specified type of striation in any one gas, the numerical value of $m$ being about 0·4.

The difference in potential between successive striae has been found in argon and neon by moving the anode along the tube so as to extinguish one striation after another, and measuring simultaneously the difference in potential between the anode and cathode, the current being meanwhile held constant. The decrease in the difference in potential, divided by the number of striations which had disappeared, was taken to be the difference in potential between successive striations. In both gases this was independent of the current (0·3 $m$A — 1·5 $m$A), and of pressure (0·25 mm. — 0·43 mm. for argon, and 0·6 mm. — 2·0 mm. for neon), and had a value of 11·9 volts for argon and of 18·5 volts for neon. Both numbers are close to resonance potentials of the gases. In hydrogen, analysis with an exploring electrode used accurately (Chap. IV) has yielded less simple results, a potential difference of 11 volts being found at a pressure of 0·99 mm., and one of 30 volts at 0·625 mm. In mercury vapour, a difference of 6 volts has been found by the same method in one instance.

The first accurate measurements of the field in a striated column were made from the deflection of a beam

of cathode rays shot across the discharge, the apparatus employed being essentially that used for study of the cathode dark space. It was found that the deflection was usually towards the cathode just to the cathode side of the bright head of a striation, but that it changed abruptly to a larger positive deflection towards the anode in the head of the striation itself. The electric field is thus reversed in places, and by Poisson's relation there must be a negative space-charge at the head of the

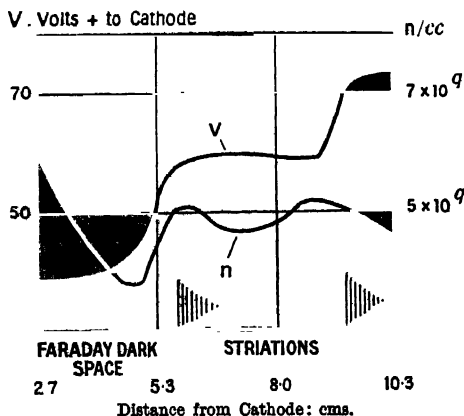



FIG. 33.—Discharge (50 milliamps.) through Helium at a pressure of 0·5 mm.

striation, and also, from the detailed appearance of the field-position graphs, a feebler positive space-charge in the dark parts between the striae.

These observations have been confirmed later by measurements with a probe wire used in the correct manner (Chap. IV), in mercury, helium and hydrogen. Fig. 33 illustrates the usual type of variations found for the potential (V), and the concentration of electrons ($n$); the potential changes rapidly near the head of the striation, and there occurs simultaneously a sharp maximum in the energy of the electrons—not shown

on the graphs—and a weaker maximum in their concentration. The maximum concentrations are of the order of $10^{10}$ per c.c., and the maximum energies about one-half to two-thirds of the ionization potential of the gas. The potential curve again shows that there is an accumulation of negative electricity at the heads of the striae, and a feebler positive space-charge elsewhere.

Any theory of the striated column will have to account for these observations, and for the great effect of certain impurities (§ 23). The primary factor in the production of striations is certainly the effect of an inelastic collision upon the speed of an electron. As has been mentioned several times, electrons describe tortuous paths under the conditions that are now being considered, and have merely a drift velocity, that is usually relatively small, superposed by the action of the electric and diffusion fields upon a larger random thermal motion. The greater the thermal motion, the less is the drift velocity imparted by a given electric field, in which electrons of small temperature will therefore contribute more to the drift current, but less to the negative space-charge, than electrons of higher temperature. The contribution of the positive ions to the drift and random currents is again negligible compared with that of the electrons. The picture to which this leads is one of slow electrons starting off with a large velocity of drift from the bright part of one striation, moving towards the anode, and —if we assume, as is practically true, that the field is almost uniform—acquiring on the way an increased temperature, but a decreased drift motion. At a certain stage, their thermal energies have become so great that their collisions with the gas-molecules cease to be elastic, and give rise to a formation of excited atoms, or of ionization, either directly or by a cumulative process. The electrons have now a greatly reduced energy, those which have suffered inelastic collisions having performed work in the act, whilst those which have been formed in the collisions are naturally slow, and so they move away with a relatively rapid drift motion until they

again make inelastic collisions at a point nearer the anode. Layers in which there are great concentrations of excited atoms and ions thus result, and are the bright parts of the striations. Immediately before the electrons make inelastic collisions they have their maximum temperature and minimum drift velocity, and hence there is, as is observed, a local negative space-charge, the corresponding positive space-charge being spread over most of the region between the bright parts. A further effect of the negative space-charge is to concentrate the direct electric field there, and so stabilize conditions by augmenting the ionization and excitation in this region. The effective field between the bright heads includes that equivalent to the forces of diffusion, the concentrations of ions and electrons falling off because of ambipolar diffusion to the walls, and perhaps, to a slight extent, because of recombination in the gas phase.

Two subsidiary conditions must be satisfied for striations to form. The first is that the initial production of excited atoms should occur within a limited region, for otherwise a spatially diffuse general emission of radiation will occur as they return to their normal states, with a consequent disappearance of the striae. This is taken care of both by the effect of the concentration of the field at the heads of the striae, and by the fact that the excitation function usually falls off fairly rapidly above an excitation potential. The continuous luminous background upon which striae are sometimes seen to be superposed may be partly due to excitation by electrons which have passed the heads without undergoing inelastic collisions.

The second condition is that large numbers of atoms in excited, particularly metastable states, must be suppressed, except at the heads of the striae. A metastable state is one which has, because of the particular set of orbital electrons associated with it, an unusually long average life before it passes spontaneously into another state with emission of radiation. The average life of a metastable neon atom may be as high as $10^{-2}$ sec.,

whereas that of a neon atom in an ordinary excited state is nearer $10^{-8}$ sec. Metastable atoms may be of great importance in connexion with sparking (§ 5). Such atoms tend to diffuse fairly uniformly through the space between the bright parts of the striations; an atom which is excited requires less energy to effect its ionization than does one which is in the normal state, and so ionization of diffusing excited atoms could be brought about by slow electrons practically anywhere in the positive column. The localization of the processes at the heads of the striae would no longer occur, and the striae, whose existence we have seen to depend upon this, would disappear. These considerations should account for the difficulty of producing striations in very pure inert gases and in mercury, where there are no impurities to destroy the diffusing excited (particularly metastable) atoms by collisions of the second kind, and several experiments made with mercury have confirmed the theory. In pure mercury vapour, the positive column is uniform. Addition of a little hydrogen gives good striations, but addition of small quantities of helium is without effect. This is entirely in accord with theory, since the energy of most of the excited mercury atoms is some 5 volts, which is well below the least excitation potential of helium at 19·7 volts, whereas it has been shown by other experiments that excited mercury is rapidly destroyed by hydrogen, the molecules of the latter becoming dissociated into atoms. The presence in these circumstances of active hydrogen in the bright parts of the striations has been shown—

(*a*) by the formation there of the compound mercury hydride (HgH), which was detected by its band-spectrum;

(*b*) by inserting in the tube a shallow tray containing white tungsten oxide. This turned blue in the bright parts of the striae, showing that a powerful reducing agent (H), was present.

The presence in the striae of excited mercury atoms was also demonstrated directly by the characteristic

absorption spectrum to which they gave rise when light was passed transversely through the tube.

The actual conditions in the striated column must often be more complicated than those we have pictured. It has, for example, been found that electrons acquire a large velocity of drift between striae (§ 19), and it is also highly questionable if the mere variation of the excitation function with the speed of the electrons will explain completely such complicated appearances as those of double striations in hydrogen. The difference in potential between neighbouring striae can also be an excitation or ionization potential only under specially favourable conditions, both because of the frequent occurrence of reversed fields, and because of the integrated effect at higher pressures of the small losses of energy suffered by the electrons in their elastic collisions with molecules between the heads. Finally, collisions of electrons with polyatomic molecules, even below the excitation potential, are generally not completely elastic.

## 25. Moving Striations

When a glow discharge starts, a luminous patch forms on the anode in the gas phase, and moves away towards the cathode, coming to rest in the position of the negative glow. This is followed by other balls, which move out till they occupy the various luminous parts of the discharge between the negative glow and the anode, the whole set of phenomena being strongly reminiscent of those observed with steady currents of small magnitude (§ 7). When an apparently uniform positive column has been established, it is however sometimes found that this too consists in reality of a series of luminous pulses moving generally in the direction anode to cathode, but occasionally in the opposite sense. These moving striae are found in the inert gases, and are best shown with the high current densities obtained on passing a current of the order of an ampere through a capillary tube. They are frequently seen in large commercial neon lamps. The simplest method of examining them

is to photograph the tube by reflection from a plane mirror which is rotating about an axis parallel to the direction of motion of the striae, which then appear tilted on the plate (Fig. 34); their velocity can be calculated at once from the speed of rotation of the mirror, and from the angle of tilt. It is usually of the order of the velocity of sound, and since there is no Doppler effect in the light emitted longitudinally from the moving column, the striae are probably due to a species of wave in the ionized gas, rather than to any transport of matter through it. The speed is somewhat less near the anode than near the cathode, and varies roughly in inverse proportion to the pressure, but its dependence upon the current is not known with certainty. It has been pointed

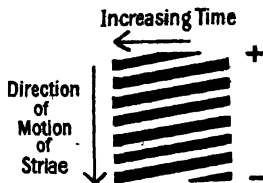



FIG. 34.—Moving Striations

out that when, as is sometimes the case, two sets of moving striae are present in the column simultaneously, their superposition might give the appearance of a stationary striated column.

The current associated with the moving striae has an oscillating component superposed on a steady component, the relative amplitudes of the two depending on the conditions of discharge. When a hot filament is used as cathode, there is a maximum value of the current in the circuit as each bright flash reaches the latter electrode. A satisfactory theory of these striae has not yet been developed, but since the frequency of the alternating component of the current is unaffected by the insertion of large capacities and inductances in the circuit, they are probably closely connected with ionic oscillations.

# CHAPTER VII

## MISCELLANEOUS PHENOMENA

### 26. The Action of Magnetic Fields

THEORETICALLY a magnetic field can affect discharge in two distinct ways. In the firs the mere presence of the field causes molecules whic have a magnetic moment to set with their axes in finite number of directions relative to the field, fixed b quantum conditions; this effect is unimportant in th discharges now being considered. In the second, th trajectories of the ions and electrons are altered. . magnetic field H acts upon a charge $e$ moving with component of velocity $v$ perpendicular to H with a forc H$ev$ which is perpendicular to both H and $v$. An component motion of the charge which is parallel t H is unaltered, and the particle thus moves in a heli of radius $r$ described round the direction of H as axi where

$$r = mv/e\mathrm{H} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2$$

The effects which we have to consider are due primaril to electrons for which, employing e.m. units,

$$r = 5{\cdot}65\ 10^{-8}\ v\mathrm{H}^{-1} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2$$

or since $v = 6{\cdot}23\ 10^{5}\ \mathrm{T}_e^{\frac{1}{2}}$ cm. per sec. . . (2

$$r = 3{\cdot}5\ 10^{-2}\ \mathrm{T}_e^{\frac{1}{2}}\ \mathrm{H}^{-1}\ \mathrm{cm.} \quad . \quad . \quad . \quad . \quad (2$$

The direction of motion of the electron is clockwi as seen in the direction of H.

If now an electric field X is applied perpendicular H, its action is to superpose upon the circular motic due to the magnetic field a motion of average spe X/H in a direction which is perpendicular to both

and X, and the question therefore arises as to how a current can pass at all along a tube in a transverse magnetic field. The reasons for this are—

(*a*) the disturbing effect of collisions between electrons and gas-molecules; and

(*b*) the effects of the walls of the tube.

To form a picture of the effect of gas, it can be assumed, probably with fair accuracy in this connexion, that each time an electron collides with a molecule of the gas, it loses its drift component of velocity, and also, as it were, its sense of direction, and starts off again in an arbitrary direction with the root mean square velocity appropriate to the electron temperature $T_e$. Each collision thus gives it a chance to move forward a distance not greater than $2r$ (equation 27) in the electric field, and it can be shown that the average direction of motion of the electron makes an angle A with the electric field, where

$$\tan A \doteq 28{\cdot}4\ H l T_e^{-\frac{1}{2}} \quad . \quad . \quad . \quad . \quad (28)$$

$l$ being the mean free path of the electron, and also that the drift velocity along the direction of the electric field is reduced in the ratio of unity to $1 + \tan^2 A$. The hindering effect of H upon the drift motion is evidently greatest at low pressures, and to take a definite example, if $l$ is 30 cm., corresponding to saturated mercury vapour at 20° C., $\tan^2 A$ is equal to 24 $H^2$, and a field of only one gauss will lower the drift velocity to 4 per cent. of its value in absence of the field.

The effects of the walls are somewhat more complicated. They are covered with a sheath of positive ions, from which an electron directed towards the inner negative charge on the solid boundary is reflected more or less specularly. Electrons thrown into the sheath by the combined action of X and H are therefore rejected, and creep along the outer boundary of the sheath in some such way as is indicated in Fig. 35, with an average velocity of drift which is but little different from that which they would have had if H had been zero. A diffusion effect also comes into play; the

electron concentration near the walls is now (cf. Fig 36) greater than that at the axis of the tube ; this part of the periphery of the conducting column must therefore become negative with respect to the axis, and so create a radial electric field which draws positive ions across as well to the place where the electron concentration has been increased, till the resultant space-charge there is again almost zero. The combined effect of this radial field and of the transverse magnetic field will be to assist the motion of the electrons in a direction normal to both, that is, towards the anode, again leading to an action tending to counteract the throwing of electrons laterally by the magnetic field alone.

Experiments have shown that these theoretical predictions are essentially correct, although other stil

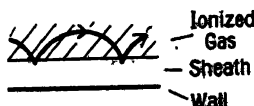



FIG. 35.—Motion of Electron reflected from Positive Ion Sheath

incompletely explained effects have also been observed. A field parallel to the axis of a tube passing an arc through mercury vapour, along the region occupied by the positive column, is without apparent action ; but if an obstacle is introduced, it throws a shadow towards the anode, since the average motion of the electrons is helical along the magnetic lines of force. The effects of a transverse field are less simple. A small local field presses the discharge against the side of the tube (Fig. 36). Larger fields cause striations to form in the constricted part, their appearance being somehow associated with the presence of a side tube near the constriction. At a critical field strength, which depends upon the conditions of discharge, a brilliant longitudinal strip, a few millimetres in width, suddenly appears running through the constricted column. The fall in potential

across the tube increases, because of an increase of the longitudinal field in the constricted part, and the expected radial field is also found to be present. Outside of the main arc path, the distribution of velocities amongst the electrons is no longer Maxwellian. A more detailed analysis makes it possible to calculate the mean free paths of the electrons from the experimental data. This proves to be only some 10 per cent. of its kinetic theory value, so that other types of effective collisions besides simple impacts with molecules must occur, for which there is independent evidence.

A transverse field makes the units of a striated column come closer together, and produces the asymmetry in their position relative to the axis which would be expected from the preceding analysis. A field of 200

Fig. 36.—Constriction of a Positive Column by a Local Transverse Magnetic Field passing normally down through the Paper

gauss has been recorded to diminish the separation in hydrogen, for example, from 2·9 cm. to 0·6 cm. in one instance, with an accompanying increase in the average potential gradient through the column. In a freshly set up tube asymmetrically placed striae may form spontaneously, and rotate slowly round the axis of the tube, presumably under the action of the magnetic field of the earth, and other stray fields of small magnitude. In a discharge between coaxial cylinders, spiral striae appear between the cathode dark space and the anode, if a symmetrical magnetic field is applied parallel to the axis to the discharge, as is indicated in Fig. 37 where the lines of magnetic force are perpendicular to the paper, their positive direction running from front to back. Even more complicated patterns have been recorded with less simply situated electrodes, and with

insulated pieces of metal and glass projecting into the discharge.

The part of the negative glow remote from the cathode is shifted towards one side of the tube in exactly the same way as the units of the positive column, that is, in a sense determined by cathode rays moving through it towards the anode. The cathode glow is unaffected by a transverse field, as is also the normal cathode fall of potential. The thickness of the cathode dark space diminishes, however, as the transverse field is increased, and tends asymptotically to a value of rather less than a millimetre in all gases, although if it is initially thinner than this, it is not affected at all. There is simultaneously a rise in the current density of about the same value as that which would have been found if the dark space had been caused to contract by other means. The theoretical significance of these observations is uncertain.

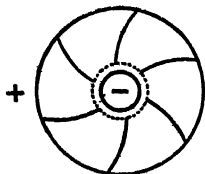



FIG. 37.—Spiral Striations in Magnetic Field

## 27. Polarization of Light Excited by Electron Impact

When a gas at very low pressure is excited by bombardment with electrons, it is found that the light emitted is partly polarized. In the case of mercury vapour, excited by 20-volt electrons, there is strong polarization of the ultra-violet resonance line (2537 A), with the electric vector perpendicular to the direction of incidence of the electrons, and strong polarization of the yellow lines (5770 A, 5791 A), with the electric vector parallel to the electron stream. A magnetic

field in the direction of the electron stream is without effect, but weak fields in a perpendicular direction cause both considerable depolarization and rotation of the plane of polarization. Somewhat similar effects are produced when the resonance line is excited by exposing mercury vapour to polarized light of the same frequency, and the depolarizing effect of a magnetic field is again marked. In the discharge tubes with which we have been concerned, these processes probably occur to a certain extent; but the net effect vanishes, since the exciting electrons and quanta are moving in almost random directions, and, in addition, a depolarization is produced under the influence of the more frequent collisions which take place between atoms at the higher pressures involved.

## 28. Pressure Effects

Differences of pressure are found to be set up between the parts of a discharge tube. At very low average pressures, the pressure at the cathode exceeds that at the anode, but at higher pressures the reverse is the case. There is some uncertainty as to the reality of the low-pressure effect, but it might be connected with an accumulation of gas brought about in the process of neutralization of positive ions at the cathode. The effect at higher pressures, however, has been studied in detail both theoretically and experimentally. The difference in pressure increases with the current and with the length of the tube, as well as with the molecular weight of the positive ions, and is less at higher pressures, but greater in narrow tubes than in wide tubes. It also increases with the longitudinal potential gradient. The order of magnitude of the effect can be gauged from the value of the pressure gradient which was given by a current of 0·16 amp. passing through argon at a pressure of 600 bars in a tube of 3 mm. radius, which was 2 bars per cm. The pressure difference is primarily set up by the positive ion sheath on the walls. In the body of the positive column, where there are as

many positive ions as electrons, the total momentu
imparted to the neutral gas-molecules—which constitu
the majority of the gas-particles present—by the positi
ions moving towards the cathode is equal and oppos
to that imparted to them by the electrons moving
the opposite direction, since both positive ions a
electrons are moving with an average non-accelerat
motion under the action of the longitudinal field. (
the other hand, at the periphery of the tube, m
momentum is conveyed to the walls across the shea
by the positive ions than by the electrons, and th
is a corresponding reaction upon the gas, tending
move the latter towards the anode. This sets up
increase in pressure at the anode, which can now
in one of two ways. If the mean free paths of t
particles concerned are greater than the radius of t
tube, the reaction upon the gas is distributed fai
uniformly across the cross-section, and the differe
of pressure between the ends of the tube is a pur
static effect. If the mean free paths are small co
pared with the radius, the reaction on the gas is confi
to a narrow layer close to the sheath, along which th
is then a bodily movement of gas towards the ano
compensated by a flow towards the cathode from t
anode in the middle of the tube. If a mixture of ga
is present, the effect is found to be specific, and has b
used to effect a partial separation of mixtures of t
inert gases, the less dense component concentrat
itself at the anode.

## 29. Optical Methods

Analysis of a discharge by a collector gives no dir
information about the concentrations of atoms and m
cules which have become excited without actually los
an electron. The existence of such atoms in the
charge is of course evident from the nature of the rac
tion emitted from it, and can also be demonstrated
its absorption of light, as has been mentioned in c
nexion with striations (§ 24); an atom which is in

excited state can absorb a quantum of radiation, which renders it more highly excited. This can be shown very clearly by passing a beam of white light through the positive column of a heavy discharge in neon; dark lines, similar to the solar Fraunhofer lines, appear on the continuous background of the spectrum of the transmitted radiation, having their origin in the absorption of radiant quanta of corresponding frequencies by certain neon atoms which were already in excited states. Another aspect of this type of absorption has also received some attention. Both on classical theory and on quantum theory, the refractive index of a medium, which normally varies in a uniform way with wave-length, should change in a more complicated but perfectly definite way near an absorption line, the phenomenon being that of anomalous dispersion. The change in refractive index can be followed, even in cases where it is small, by delicate interferometric methods. Jamin blocks have been employed (cf. W. E. Williams, *Applications of Interferometry*), and from the magnitude of the anomalous effect, the number of excited atoms responsible for the absorption can be calculated. Very few investigations of ionized gases have yet been made by this method, but the results obtained from them for excited atoms are in reasonable agreement with the results for ionized atoms, such as have been discussed in preceding chapters, concentrations of from $10^{11}$ to $10^{12}$ per c.c. being found, for example, for certain excited neon atoms, under conditions where the concentration of neon ions was probably about $10^{11}$ per c.c. It seems likely that systematic measurements of the dependence of concentration upon current density and gas-pressure will lead to a better understanding of the conditions of equilibrium in the positive column.

A somewhat similar method has also been used to find by optical methods the concentrations of positive ions. We may consider the special case of mercury. Singly charged positive ions of mercury, like the neutral atom, have a normal state, and sets of excited states,

and it is known that the resonance line of the mercury ion, corresponding to the simplest transition between the excited system and the normal state, occurs in the ultraviolet at 1941·5 A. This line is emitted strongly by a low-voltage arc in a mixture of mercury vapour and neon, but is not emitted in appreciable intensity by the positive column of a glow-discharge through mercury vapour. The latter, however, since it contains numerous unexcited ions, is able to absorb this line. If then the spectrum of the light from a low-voltage arc is taken first directly, and then after transmission through the positive column under otherwise identical conditions, the resonance line of the positive ion should be feebler on the second exposure than on the first, as is in fact found to be the case. In the actual experiment some argon was added to the mercury vapour to facilitate the passage of the discharge through it. From the weakening of the line, the concentration of the positive ions responsible for its absorption can be calculated approximately, yielding results which agree with those obtained directly by the use of collectors. For example, about $2 \cdot 10^{10}$ ions per c.c. were found by this means to be present in the positive column of a discharge through mercury at a pressure of 3 mm. mixed with argon at a pressure of 0·25 mm., in a tube 1·3 cm. in radius passing a current of 0·1 amp. at 150 volts.

# APPENDIX

## IMPORTANT REFERENCES

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